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Monitoring Completed Navigation Projects Program

Periodic Inspection of Ofu Harbor Breakwater, American Samoa

Armor Unit Monitoring for Period 1996-2002

Robert R. Bottin, Jr., and Daniel T. Meyers

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by Robert R. Bottin, Jr.

Coastal and Hydraulics Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Daniel T. Meyers

U.S. Army Engineer District, Honolulu
Building 230
Fort Shafter, HI 96858-5440

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Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in figures, plates, and tables of this report can be converted to SI units as follows:

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic yards	0.7645549	cubic meters
degrees (angle)	0.01745329	radians
feet	30.48	centimeters
feet	0.3048	meters
inches	0.0254	meters
inches	2.54	centimeters
miles (U.S. statute)	1.609347	kilometers
pounds (mass)	0.4535924	kilograms
square miles	2.59	square kilometers
tons (2,000 pounds, mass)	907.1847	kilograms

Preface

The study reported herein was conducted as part of the Monitoring Completed Navigation Projects (MCNP) Program, formerly Monitoring Completed Coastal Projects Program. Work was carried out under Work Unit 11M-7, "Periodic Inspections." Overall program management for MCNP is accomplished by Headquarters, U.S. Army Corps of Engineers (HQUSACE). The Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Research and Development Center (ERDC), is responsible for technical and data management support for HQUSACE review and technology transfer. Technical Monitors for the MCNP Program are Messrs. Barry W. Holliday, David B. Wingerd, and Charles B. Chesnutt, HQUSACE. The Program Manager is Mr. Robert R. Bottin, Jr., CHL.

This report is part of a series that will track the long-term structural response of the Ofu Harbor breakwater, American Samoa, to its environment. The information contained in this report was gathered as a result of land and aerial survey work conducted by Richard B. Davis, Inc., under contract to the Corps of Engineers, and an armor unit survey conducted by Mr. Bottin and Mr. Daniel T. Meyers, U.S. Army Engineer District, Honolulu.

The work was conducted during the period May through August 2002 under the general supervision of Mr. Thomas W. Richardson and Dr. William D. Martin, Director and Assistant Director, CHL, and under the direct supervision of Mr. Dennis G. Markle, Chief, Coastal Harbors and Structures Branch. This report was prepared by Messrs. Bottin and Meyers.

Director of ERDC during the investigation and publication of this report was Dr. James R. Houston. Commander and Executive Director was COL John W. Morris, III, EN.

1 Introduction

Monitoring Completed Navigation Projects Program

The goal of the Monitoring Completed Navigation Projects (MCNP) Program (formerly the Monitoring Completed Coastal Projects Program) is the advancement of coastal and hydraulic engineering technology. The program is designed to determine how well projects are accomplishing their purposes and are resisting the attacks by their physical environment. These determinations, combined with concepts and understanding already available, will lead to creating more accurate and economical engineering solutions to coastal and hydraulic problems; to strengthening and improving design criteria and methodology; to improving construction practices and cost-effectiveness; and to improving operations and maintenance techniques.

To develop direction for the program, the U.S. Army Corps of Engineers initially established an ad hoc committee of engineers and scientists. The committee formulated the objectives of the program, developed its operational philosophy, recommended funding levels, and established criteria and procedures for project selection. A significant result of their efforts was a prioritized listing of problem areas to be addressed, essentially a listing of the areas of interest of the program.

Corps offices are invited to nominate projects for inclusion in the monitoring program as funds become available. The MCNP Program is governed by Engineer Regulation 1110-2-8151, Headquarters, U.S. Army Corps of Engineers (HQUSACE 1997). A selection committee reviews and prioritizes the projects nominated based on criteria established in the regulation. The prioritized list is reviewed by the Program Monitors at Headquarters, U.S. Army Corps of Engineers (HQUSACE). Final selection is based on this prioritized list, national priorities, and the availability of funding.

The overall monitoring program is under the management of the Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Research and Development Center (ERDC), with guidance from HQUSACE. Development of monitoring plans and the conduct of data collection and analyses are dependent upon the combined resources of CHL and the District/Division. The study reported herein, was completed as part of the "Periodic Inspections" work unit of the MCNP Program.

Work Unit Objective and Monitoring Approach

The objective of the Periodic Inspections work unit in the Monitoring Completed Navigation Projects (MCNP) Program is to periodically monitor selected coastal navigation structures to gain an understanding of the long-term structural response of unique structures to their environment. These periodic data sets are used to improve knowledge in design, construction, and maintenance of both existing and proposed future coastal navigation projects. These data also will help avoid repeating past design mistakes that have resulted in structure failure and/or high maintenance costs. Past projects monitored under the MCNP Program, and/or structures with unique design features that may have application at other sites, are considered for inclusion in the periodic inspections monitoring program. Selected sites are presented as candidates for development of a periodic monitoring plan. Once the monitoring plan for a site is approved and funds are provided, monitoring of the site is initiated. Normally, base conditions are established and documented in the initial effort. The site then is reinspected periodically (frequency of surveys is based on a balance of need and funding for each monitoring site) to obtain long-term structural performance data.

Relatively low-cost remote sensing tools and techniques, with limited ground truthing surveys, are the primary inspection tools used in the monitoring efforts. Most periodic inspections consist of capturing above-water conditions of the structure at periodic intervals using high-resolution aerial photography. Periodic aerial photographs are compared visually to gauge the degree of in-depth analysis required to quantify structural changes (primarily armor unit movement). Data analysis involves using photogrammetric techniques developed for and successfully applied at other coastal sites. At sites where local wave data are being gathered by other projects and/or agencies, and these data can be acquired at a relatively low cost, wave data are correlated with structural changes. In areas where these data are not available, general observations and/or documentation of major storms occurring in the locality are presented along with the monitoring data. Ground surveys are limited to the level needed to establish the accuracy of the photogrammetric techniques.

When a coastal structure is photographed at low tide, an accurate permanent record of all visible armor units is obtained. Through the use of stereoscopic, photogrammetric instruments in conjunction with photographs, details of structure geometry can be defined at a point in time. By direct comparison of photographs taken at different times, as well as the photogrammetric data resolved from each set of photographs, geometric changes (i.e., armor unit movement and/or breakage) of the structure can be defined as a function of time. Thus, periodic inspections of the structures will capture permanent data that can be compared and analyzed to determine if structure changes are occurring that indicate possible failure modes and the need to monitor the structure(s) more closely. The Ofu Harbor breakwater, American Samoa, was nominated for periodic monitoring by the U.S. Army Engineer District, Honolulu. Initial monitoring of base level conditions was completed in 1996/1997 (Bottin and Boc 1997).

Three additional Honolulu District projects have been monitored previously under the Periodic Inspections work unit. Both base conditions and subsequent inspections have been conducted for breakwaters at Kahului Harbor, Maui, HI; and Laupahoehoe boat launching facility breakwaters, HI, (Markle and Boc 1994; Bottin and Meyers 2002a) and for the Nawiliwili Harbor breakwater, Kauai, HI, (Bottin and Boc 1996, Bottin and Meyers 2002b).

Project Location and History

American Samoa is a group of seven islands (five volcanic islands and two coral atolls) located in the South Pacific Ocean. These islands lie at approximately long. 170° W. and lat. 14° S. They comprise a total area of about 200 sq km (76 square miles).[1] They are located about 6,700 km (4,150 miles) southwest of San Francisco, CA, and about 3,700 km (2,300 miles) south-southwest of Hawaii (Figure 1).

The five major inhabited islands of America Samoa are Tutuila, Aunuu, Ofu, Olosega, and Tau. Tutuila, the largest and principal island, is the center of government and business. Aunuu lies 1.6 km (1 mile) off the east coast of Tutuila. The three islands, Ofu, Olosega, and Tau, collectively referred to as the Manu'a Islands, are located 106 km (66 miles) east of Tutuila. Ofu and Olosega are often called sister islands because they are separated by less than 275 m (900 ft) of shallow reef.

The American Samoan Islands were discovered in the 1700s by Dutch navigators. However, the islands remained unclaimed until the 1900s, when the chiefs of the islands ceded title to the United States (U.S. Army Engineer District, Honolulu 1973). The U.S. Navy administered the islands as a U.S. territory until 1951, when the U.S. Department of the Interior assumed administration. Its inhabitants are American nationals, but not citizens. They may visit or emigrate to the United States without passport.

The island of Ofu has an area of about 4.8 sq km (3 square miles). It is of volcanic origin and is encircled by a fringing reef. The reef generally ranges from 300 to 600 m (1,000 to 2,000 ft) in width with depths varying from 0.3 to 1.8 m (1 to 6 ft).[2] Ofu Harbor is situated on a reef platform off the northwest coast of the island (Figure 2). The project, constructed in 1975, utilized a portion of an existing natural channel through the reef. It consisted of a 5.5-m-deep (18-ft-deep), 40-m-wide (130-ft-wide) entrance channel approximately 67 m

[1] Units of measurement in the text of this report are shown in SI units, followed by non-SI units in parenthesis. In addition, a table of factors for converting non-SI units of measurement used in figures in this report to SI units is presented on page v.

[2] All elevations (el) and depths cited herein are in meters (ft) referred to mean low water (mlw) datum.

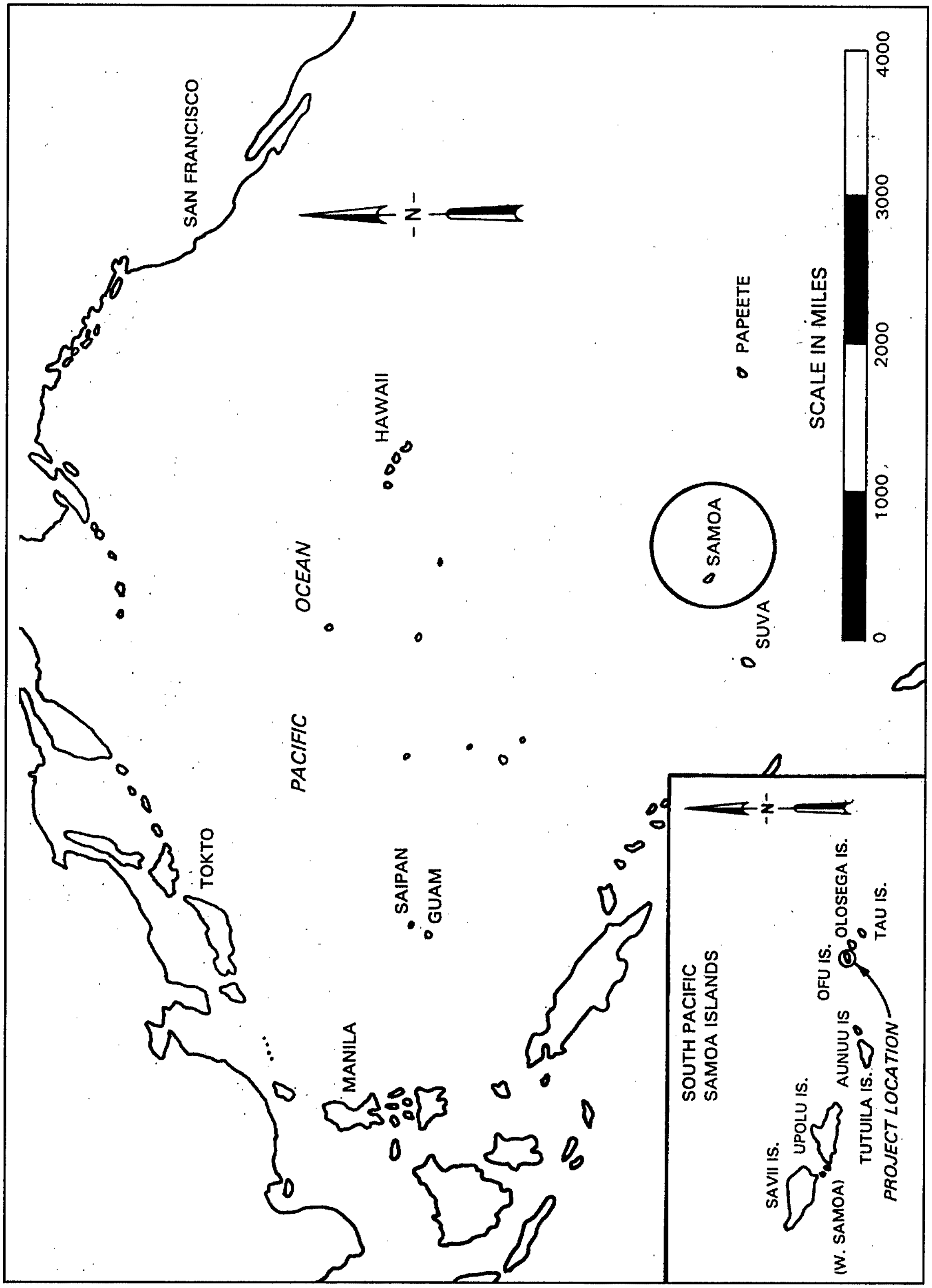

Figure 1. Location of American Samoan Islands

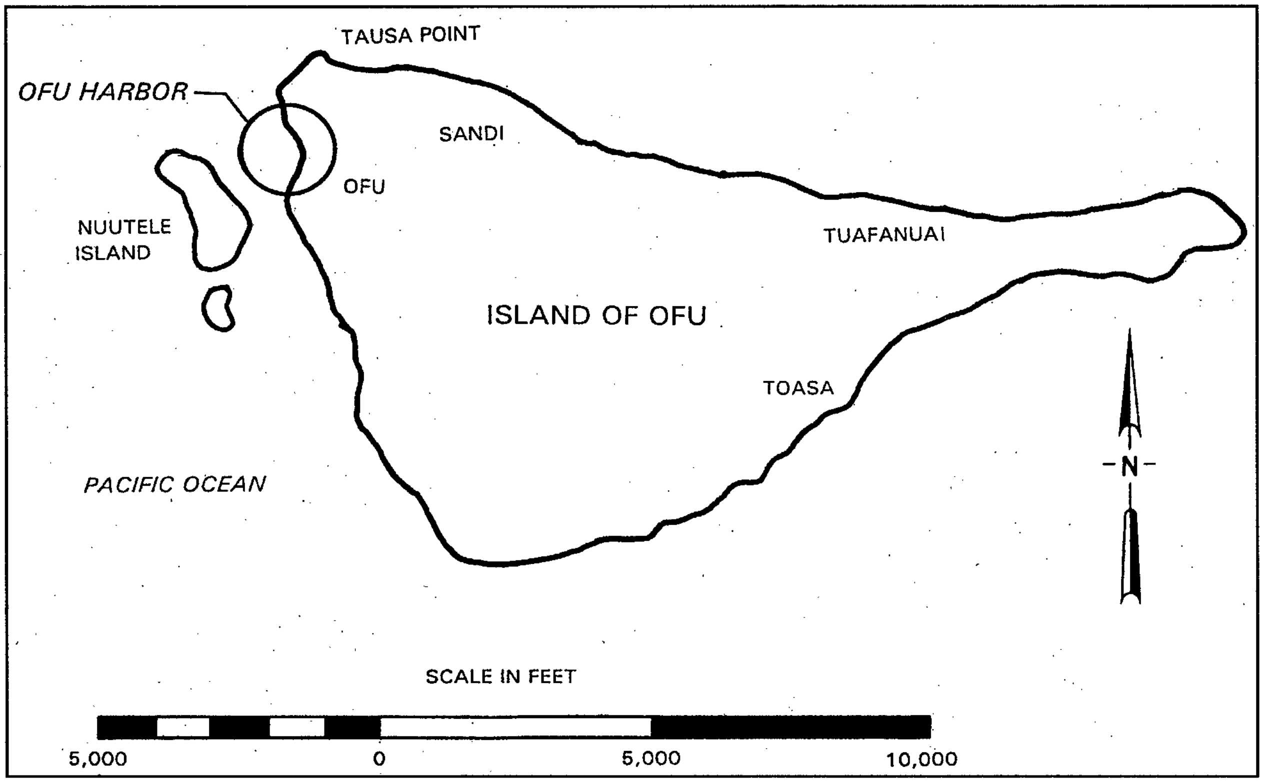

Figure 2. Location of Ofu Harbor

(220 ft) in length and a 4.9-m- (16-ft-) deep turning basin with horizontal dimensions of approximately 91 × 91 m (300 × 300 ft). Material from channel and turning basin dredging was used to construct a 12,140-sq m (3-acre) landfill adjacent to mooring areas and for protection of the harbor from wave action (USAED, Honolulu, 1973). The landfill, where exposed to wave action, was armored with a stone revetment. The revetment was placed on a slope of 1V:1.5H and consisted of armor stones ranging from 910 to 1,815 kg (1 to 2 tons) and underlayer stone ranging from 450 to 910 kg (0.5 to 1 ton). Figure 3 is a plan view of the originally constructed improvements.

In 1981, the Ofu Harbor revetment was severely damaged by tropical storm Esau, with subsequent repairs completed in 1982. Then in 1990, Hurricane Ofa struck American Samoa and the revetment again sustained severe damage. Before the structure could be rehabilitated, Cyclone Val further damaged it in 1991.

The revetment was almost completely destroyed. Armoring and underlayer stone on both the harbor and sea sides required complete repair. The entrance channel and turning basin also required dredging to remove stone and dredged landfill material washed into these areas.

The latest rehabilitation was completed in 1994 and consisted of construction of a new breakwater that extended from sta 1+75 to sta 6+10, as shown in Figure 4. The breakwater was moved back shoreward to the edge of the reef in

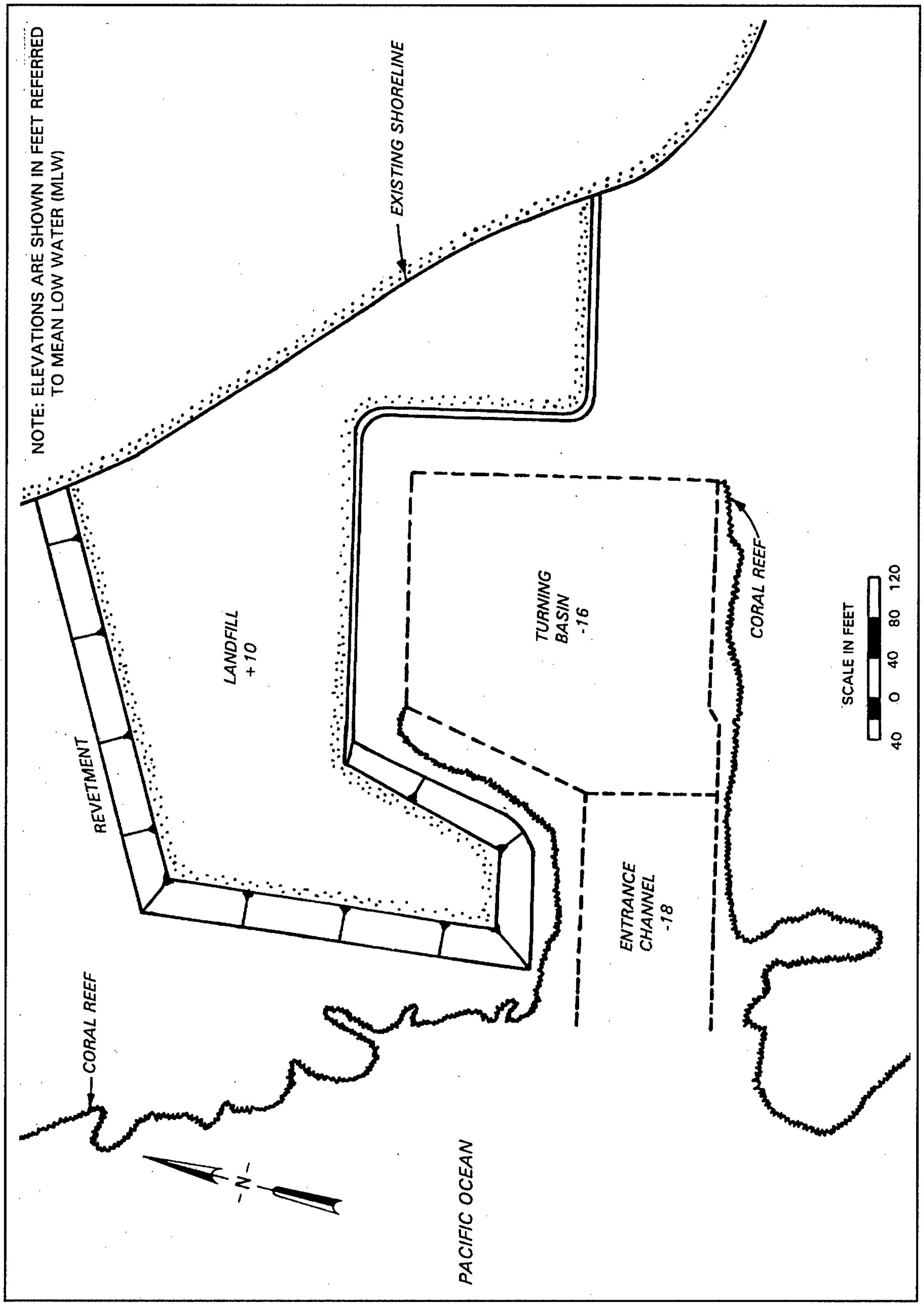

Figure 3. Original layout of Ofu Harbor, American Samoa

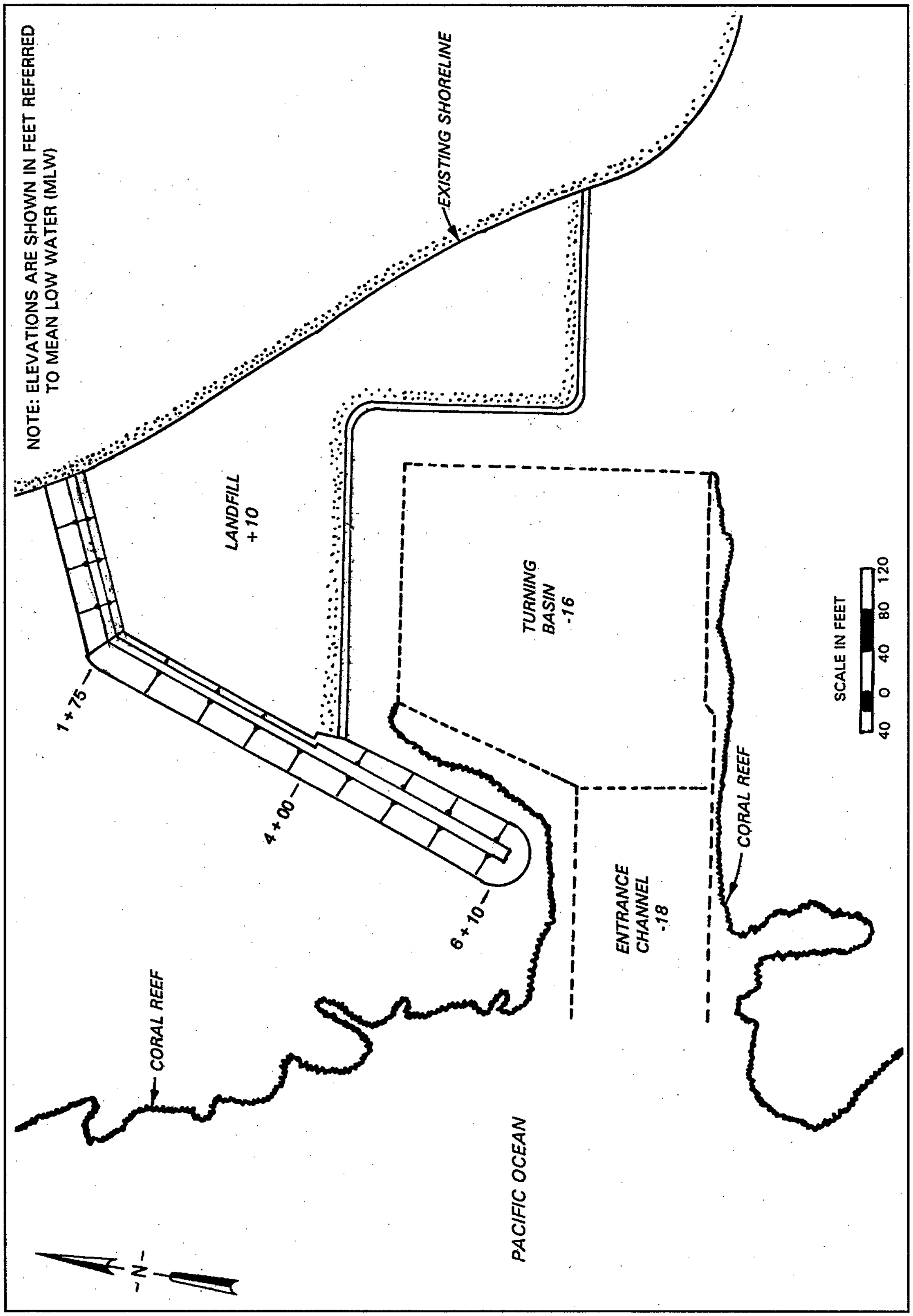

Figure 4. Layout of harbor after 1994 rehabilitation

order to provide the incoming waves more area between the reef and the structure in which to break and dissipate their energy. All loose material seaward of the new structure also was removed. The breakwater cross section was studied at ERDC for hydraulic stability (Turk 1995).

For environmental, economical, and logistical reasons, additional basalt stone material could not be obtained from either Ofu Island or Tutuila Island to construct the Ofu Harbor breakwater. Only the stones at the project site that could be salvaged were available for use in breakwater construction. The structure, therefore, was built utilizing a unique "concrete design." Basically, the design entailed using various sized concrete units for breakwater construction as opposed to using basalt stone.

The breakwater armor consisted of a single layer of uniformly-placed 4,080-kg (4.5-ton) concrete tribar units (Figure 5). The tribars originated at sta 1+75 on the seaward face of the structure and extended to sta 6+10, around the head, and then to sta 4+00 on the harbor side of the breakwater. To improve the stability of the tribars, work included the construction of a toe trench in order to stabilize the armor unit toe, and a concrete rib cap system on the breakwater crest to stabilize and buttress tribars at the upper sea and harbor side slopes. The rib cap forms were fabricated and concrete poured right into the top section of the tribars (Figure 6). The crest elevation (el) of the rib cap was +4.6 m (+15 ft), and the slope of the structure was 1V:1.5H.

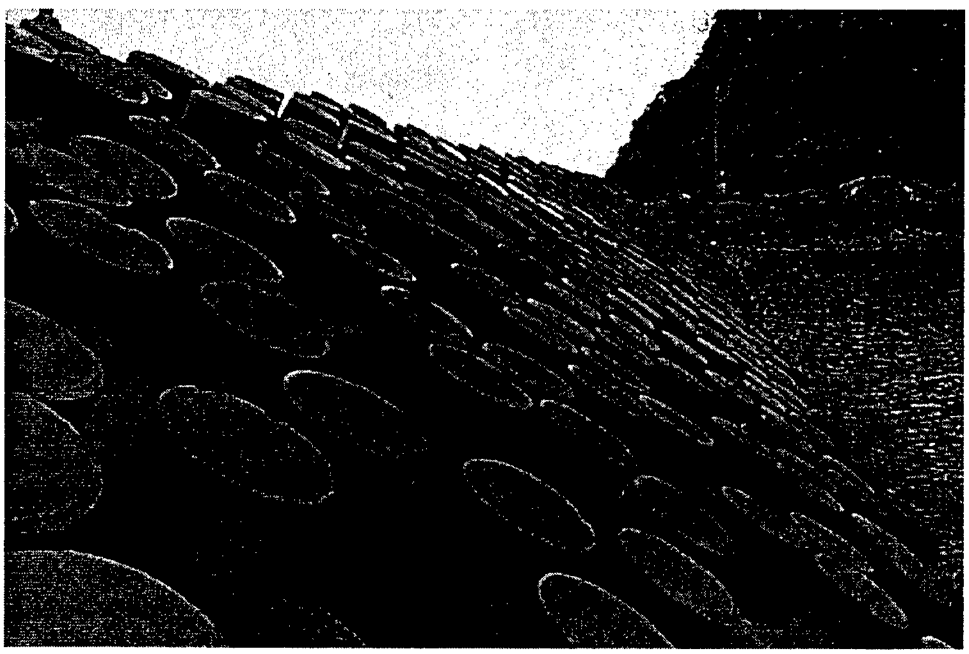

Figure 5. Tribar armor units used on Ofu Harbor breakwater

Due to the nonavailability of local stone as previously mentioned, concrete underlayer units were used during construction of the Ofu Harbor breakwater. A unique 1,635-kg (1.8-ton) concrete unit, designed and developed by the Honolulu District, was used as an underlayer for the tribars on the trunk section of the

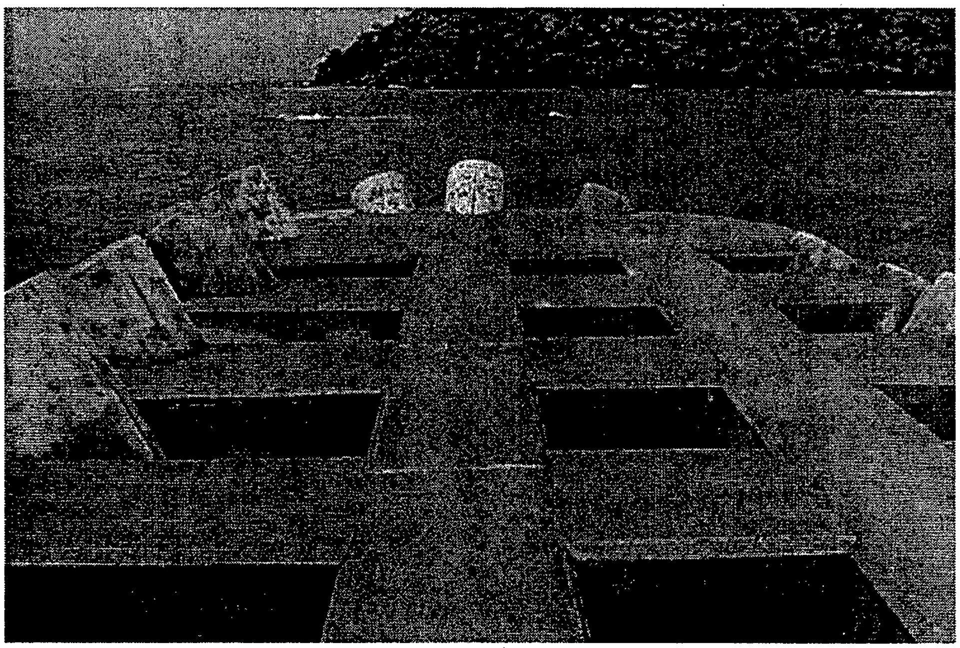

Figure 6. Concrete rib cap on crest of Ofu Harbor breakwater

breakwater. These units are approximately 1.2 × 1.2 × 0.6 m (4.0 × 4.0 × 2.0 ft) in size with chamfered corners. They have 0.4-m- (16-in.-) diameter holes in their centers with 0.23-m- (9-in.) diam semicircular holes on each side protruding through the units from front to back. When placed in a one-layer section on the breakwater slope, the holes create void spaces in which wave energy can be dissipated. The underlayer unit, with the holes, resemble a slice of Swiss cheese and has been so labeled the "Swiss cheese block." A view of the unit is shown in Figure 7.

In addition to the "Swiss cheese block" underlayer unit, both 2,270-kg and 510-kg (2.5-ton and 1,125-lb) concrete units were formed by pumping high-strength, fine-aggregate concrete into geotextile fabric bags. The 2,270-kg (2.5-ton) units were used as a rib cap underlayer and were placed along the land-fill on the harbor side of the structure between stas 1+75 and 4+00 (Figure 8). These units measured approximately 1.4 × 0.9 × 0.8 m (4.5 × 3.0 × 2.5 ft) in size. The 510-kg (1,125-lb) concrete units were used as an underlayer for the 2,270-kg (2.5-ton) units. They also were used as an underlayer for the tribars around the breakwater head since the 1,635-kg (1.8-ton) "Swiss cheese blocks" could not be placed in this area around the relatively tight radius. The dimensions of the 510-kg (1,125-lb) concrete units were about 0.9 × 0.6 × 0.3 m (3.0 × 2.0 × 1.0 ft). Typical cross sections of the 1994 breakwater construction are presented in Figure 9. An aerial view of the harbor breakwater is shown in Figure 10.

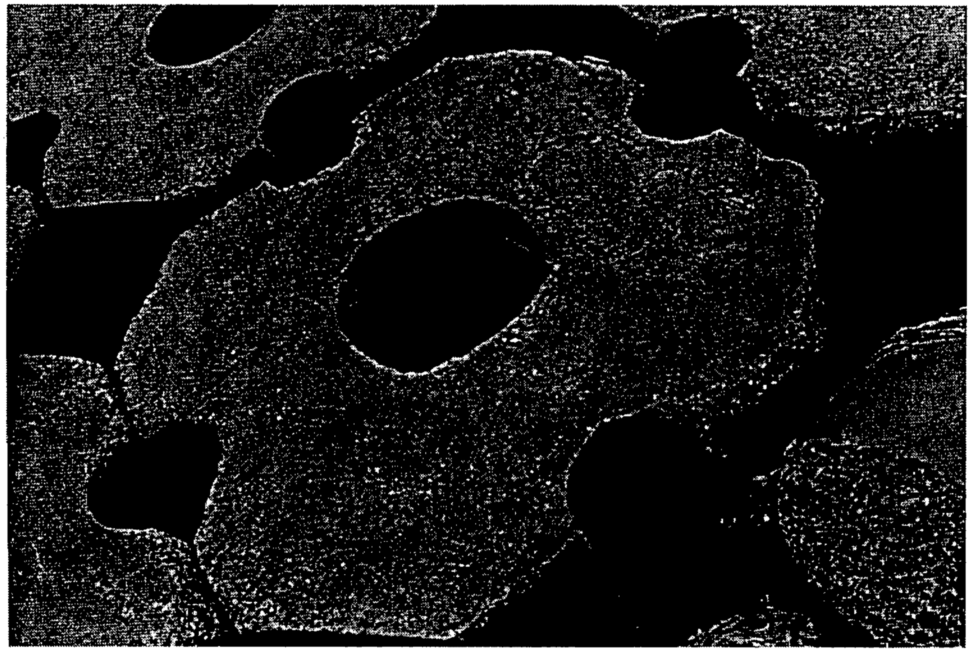

Figure 7. View of 1.635-kg (1.8-ton) "Swiss cheese block" concrete underlayer unit

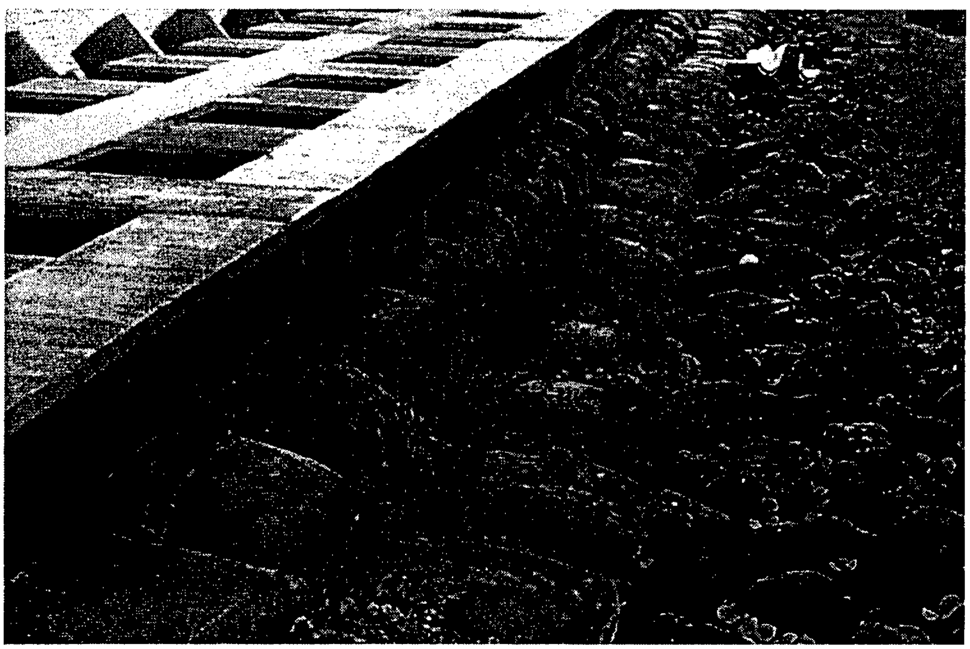

Figure 8. 2,270-kg (2.5-ton) high-strength concrete units used on harbor side of structure

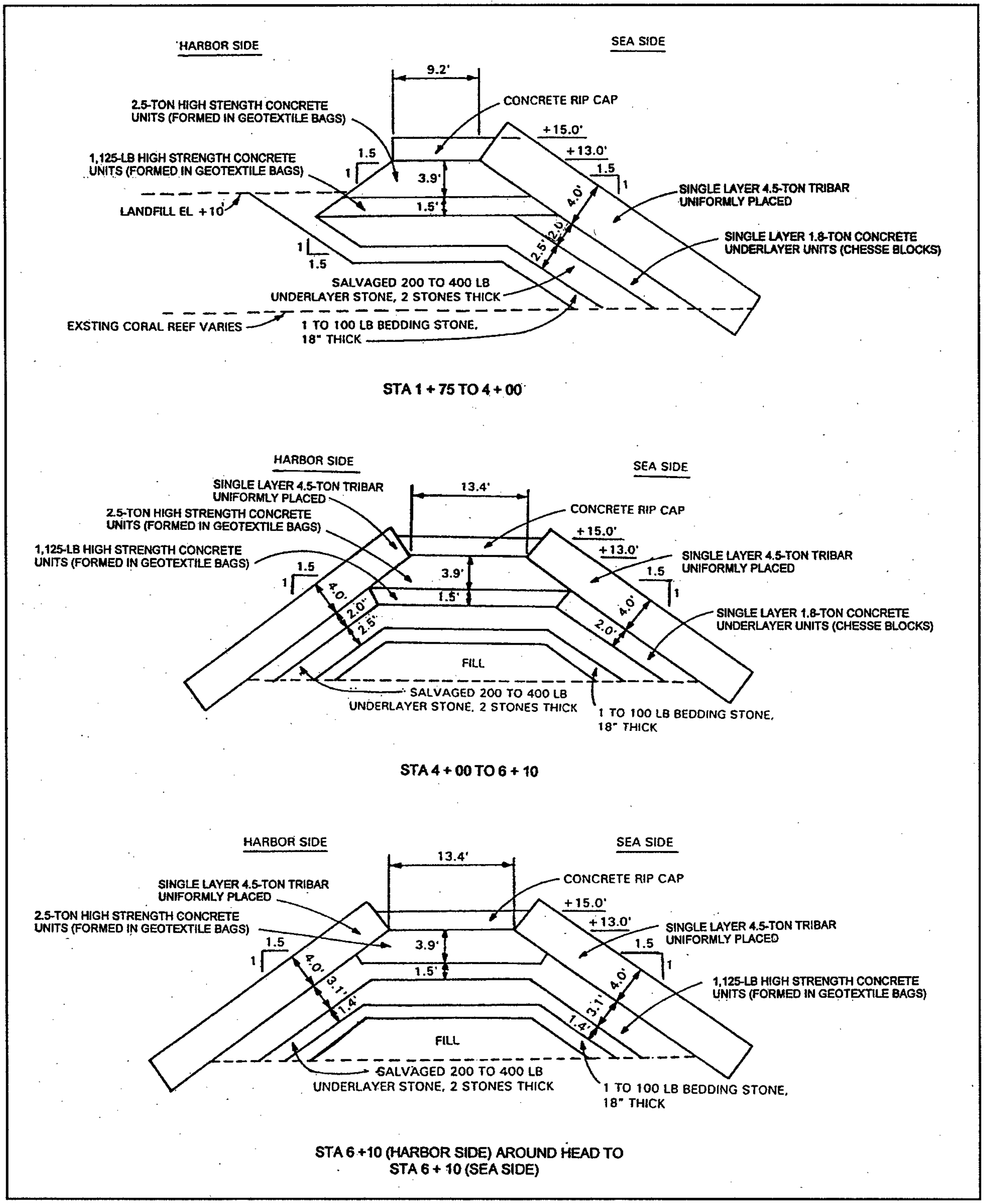

Figure 9. Typical cross sections for 1994 breakwater construction

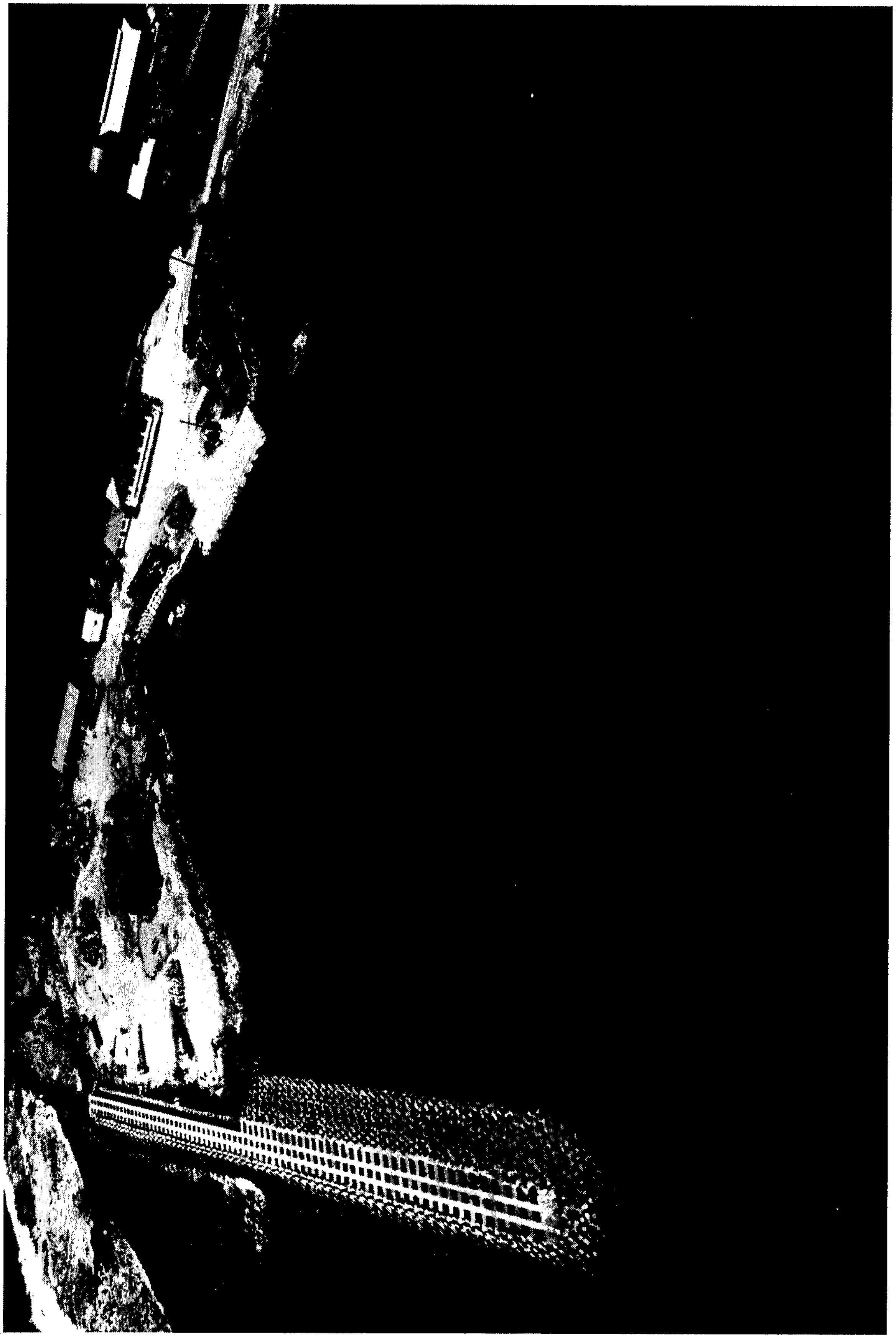

Figure 10. Aerial photograph of Ofu Harbor breakwater

Prior Monitoring (Periodic Inspection) of Site

Initial monitoring of the Ofu breakwater was completed October 1996 through June 1997 as part of the "Periodic Inspections" work unit of the MCNP Program (Bottin and Boc 1997). Work included armor unit targeting, ground surveys, aerial photography, photogrammetric analyses of armor units, and an armor unit inspection. The information obtained during the monitoring effort established base level conditions for the breakwater. Precise positions of targeted armor units were obtained as well as centroid data and orientations of the targeted armor units. The walking survey of the structure revealed no broken armor units.

Purposes of Current Study

The purposes of the study reported herein were to:

a. Apply methodology previously developed using land-based surveying, aerial photography, and photogrammetric analysis to assess the long-term stability response of the concrete armor units on the Ofu Harbor breakwater.

b. Conduct limited land surveys, armor unit inspections, aerial photography, and photogrammetric analyses to accurately define armor unit movement above the waterline.

c. Compare the breakwater's armor unit positions to those obtained during the previous survey and define changes that have occurred.

2 Monitoring Plan and Data

The objective of the current monitoring effort in the "Periodic Inspections" work unit was to re-examine the targeted armor units on the outer 132.6-m-long (435-ft-long) portion of the Ofu breakwater and determine changes that have occurred since the last inspection in 1996/1997. The monitoring plan consisted of retargeting armor units, limited ground surveys, aerial photography, photogrammetric analysis of armor units above the waterline, a ground-based armor unit survey, and comparisons of current armor unit positions with those obtained previously.

Armor Unit Survey

On 22 May 2002, a walking survey of above-water armor units was conducted on the outer 132.6-m (435-ft) portion of the Ofu Harbor breakwater. The survey of the structure revealed no broken tribars. Fifteen sea-side tribars were slightly separated from the rib cap (Figure 11). These separations ranged from 0.64 to 7.62 cm (0.25 to 3 in) and occurred on ribs 2, 12, 13, 14, 16, 20, 22, 25, 26, 32, 39, 42, 66, 67, and 71 (beginning with ribs at the shoreward end). Only one separation was noted during the previous survey at rib 22 (sta 3+07). On the entire sea-side of the structure it also was noted that some of the "Swiss cheese block" underlayer units had separated along the slope between the third and fourth rows (down from the crest). Typical separations ranged from 2.54 to 10.16 cm (1 to 4 in.), and the maximum was about 20.32 cm (8 in.). Some separations were predominantly vertical (Figure 12) while others were predominantly horizontal (Figure 13). Separations of about 2.54 to 10.16 cm (1 to 4 in.), both horizontally and vertically were also noted on "cheese blocks" on the harbor side of the structure. Separations between the "cheese block' underlayer units appeared to be more widespread during this inspection as opposed to the previous one. The geotextile bags had deteriorated and some spalling along the edges of the 510-kg (1,125-lb) high-strength concrete underlayer units was also noted around the head of the structure (Figure 14). These conditions were also noted during the previous inspection. Some slight movement in the breakwater's underlayer armor units has occurred, but in general, the breakwater appeared to be in excellent condition.

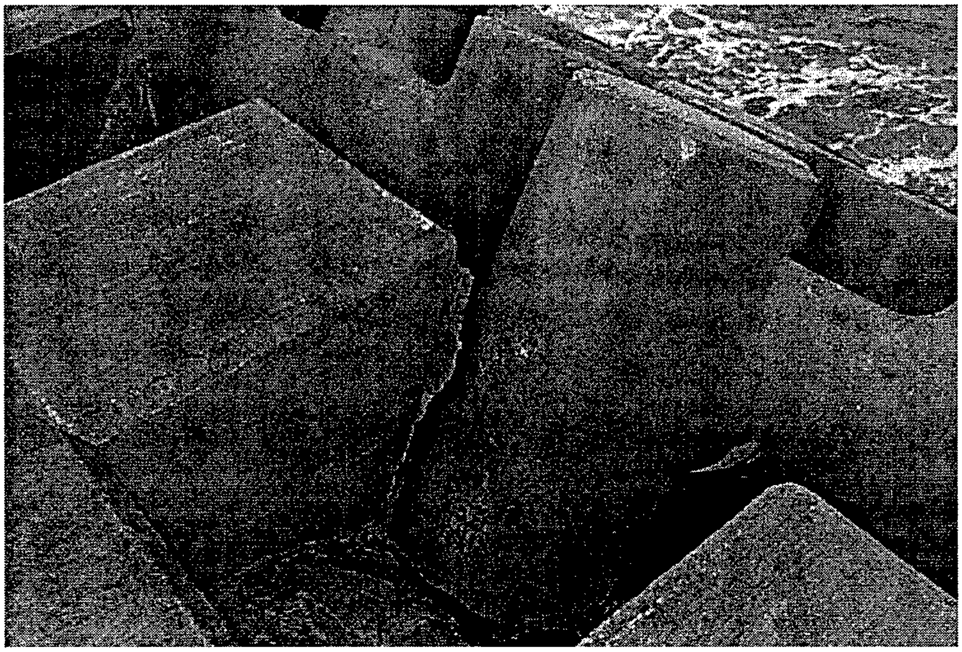

Figure 11. Separation between tribar and rib cap

Figure 12. Vertical separation between "Swiss cheese block" underlayer units

Figure 13. Horizontal separation between "Swiss cheese block" underlayer units

Figure 14. Spalling of 510-kg (1,125-lb) high-strength concrete underlayer units

Targeting and Ground Surveys

To serve as control for the ground-based survey as well as the photogrammetric work, existing monuments from previous surveys were located and resurveyed using Trimble Real-Time Kinemetic Global Positioning System (GPS) equipment and electronic surveying techniques. Positions and elevations of the monuments established on the structure are presented in the following tabulation. Their approximate locations are presented in Figure 15. Horizontal positions are based on the American Samoa Plane Coordinate System and all elevations are referenced to mean low water (mlw) datum. The initial ground survey work was conducted during the period 26-28 August 2002.

Monument	Easting	Northing	el, m (ft)
Base	613,188.21	347,960.32	+3.307 (+10.85)
X	613,448.08	347,804.85	+1.969 (+6.46)
Ramp	613,624.50	347,595.94	+0.853 (+2.80)
Cambra	613,025.90	347,707.09	+4.575 (+15.01)
Tom	613,174.65	348,117.59	+4.590 (+15.06)
XX	613,255.14	348,140.54	+4.548 (+14.92)

In addition, targets were re-established on selected concrete armor units. As previously reported (Bottin and Boc 1997), a total of 33 tribars was selected for detailed study. They represent an even distribution throughout the tribar field, and occupy positions ranging from near the waterline to close to the rib cap at the crest of the structure. These armor units (tribars 101-133) were painted with three targets (Figure 16). The target for each tribar is indicated by an A, B, or C. Three targets on an individual tribar allow for very precise measurements depicting individual armor unit movement. Twenty additional tribars (units 19-38) were painted with a single target to serve as photogrammetric control points, as well as to be used to detect armor unit movement during future ground surveys. A 0.64-cm (1/4-in.) hole was drilled at the center of each target to mark the survey points for subsequent surveys. Units were chosen for targeting that had flat surfaces close to horizontal to maximize their visibility in aerial photography and allow for accurate representation of armor unit movement. Locations of the targeted tribars are shown in Figures 17 and 18.

Aerial Photography

Aerial photography is a very effective means of capturing images of large areas for later analysis, study, visual comparison to previous or subsequent photography, or measurement and mapping. Its chief attribute is the ability to freeze a moment in time, while capturing extensive detail.

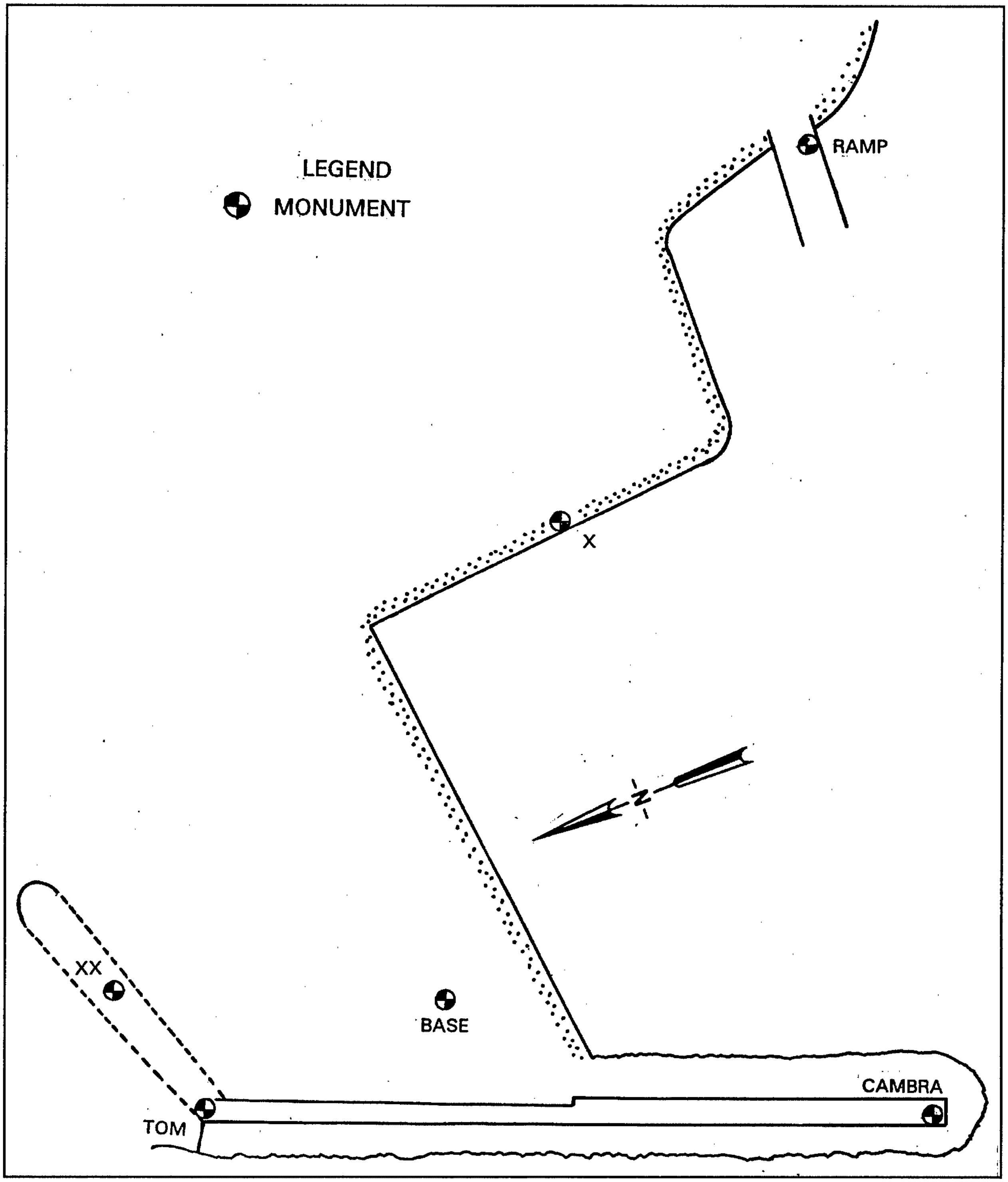

Figure 15. Diagram of monuments used for survey control at Ofu Harbor

Figure 16. View of a targeted tribar (three targets established)

Aerial photography was obtained along Ofu Harbor breakwater with a Zeiss RMK A 15/23 aerial mapping camera (9-in. by 9-in. format). Color photos were secured from a fixed-wing aircraft flying at an altitude of about 183 m (600-ft), which resulted in high resolution images and contact prints with scales of 1:1,200. Photographic stereopairs were obtained during the flight. Stereopairs secured for the breakwater are shown in Figure 19. The aerial photography was obtained on 28 August 2002.

Photogrammetric Analysis of Armor Unit Targets

When aerial photography is planned and conducted so that each photo image overlaps the next by 60 percent or more, the two photographs comprising the overlap area can be positioned under an instrument called a stereoscope, and viewed in extremely sharp three-dimensional (3-D) detail. If properly selected survey points on the ground have previously been targeted and are visible in the overlapping photography, very accurate measurements of any point appearing in the photographs can be obtained. This technique is called photogrammetry.

The stereopair images obtained during aerial photography at Ofu Harbor were viewed in a Zeiss P-3 analytical stereoplotter, and stereomodels were oriented to ground control point data previously obtained. In the stereomodel,

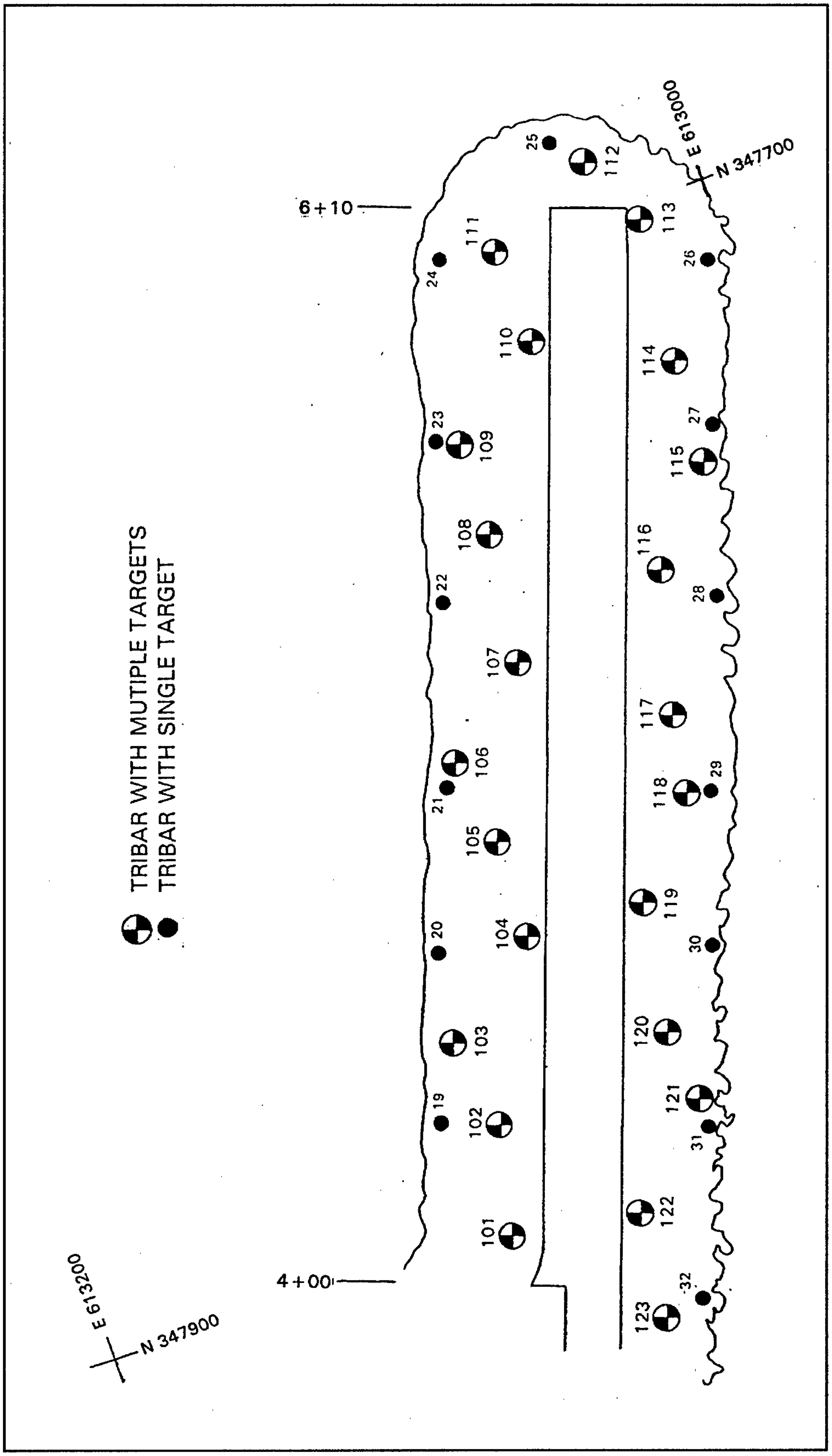

Figure 17. Location of targeted armor units on outer portion of breakwater

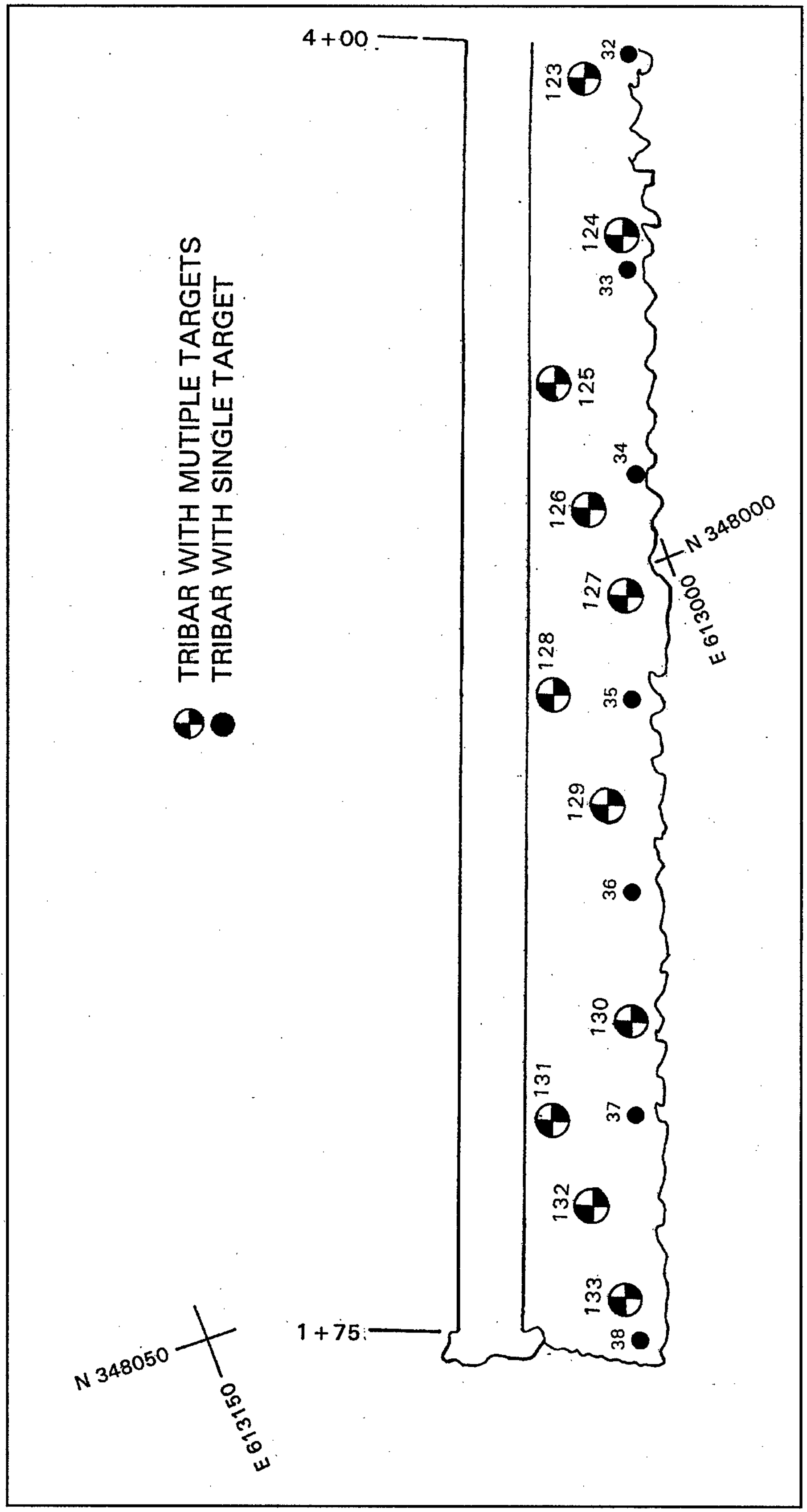

Figure 18. Location of targeted armor units on inner portion of breakwater

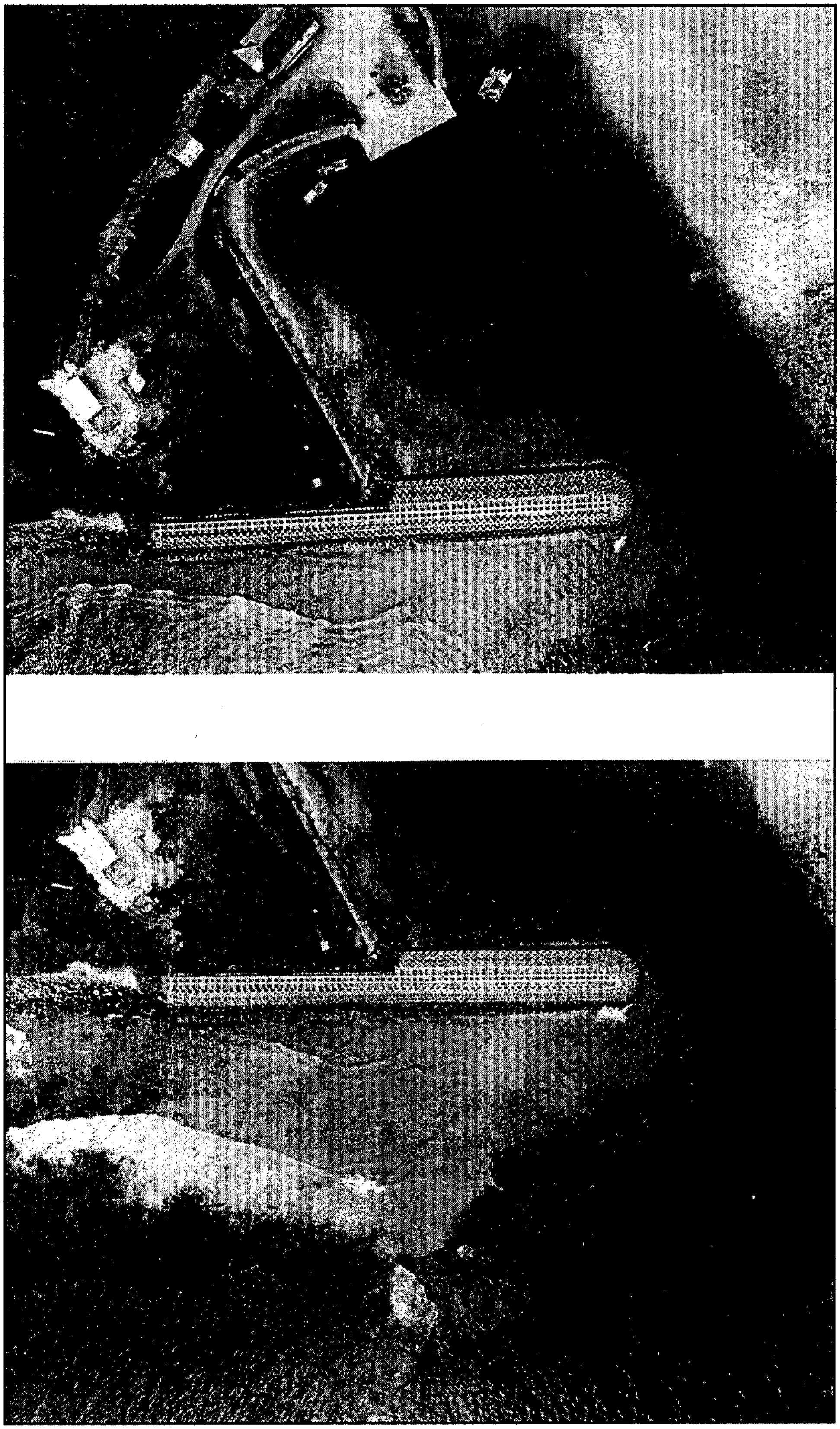

Figure 19. Stereopair photographs of Ofu Harbor breakwater

very accurate horizontal and vertical measurements can be made of any point on any armor unit appearing in the print. The stereomodel was used for all photogrammetric compilation and the development of photo maps. To establish accuracy of the photogrammetric work, comparisons of the coordinates for selected targets obtained during the ground survey with those of the aerial survey (stereomodel) were conducted and indicated very close agreement. Maximum differences were 0.046 and 0.064 m (0.15 and 0.21 ft), respectively, for the horizontal and vertical positions. An average of all horizontal and vertical positions indicated differences of 0.011 m (0.035 ft) and 0.018 m (0.06 ft), respectively.

A photogrammetric analysis of the armor unit targets was conducted and x-, y-, and z- (easting, northing, and el) coordinates were obtained for the 2002 aerial survey. The 1996/1997 aerial survey of the site was plagued by logistical problems and low-altitude, high-quality, stereopair images were not obtained. Convergent photogrammetric techniques were utilized that produced results from oblique photos that were not as precise as the vertical stereopair analysis. Therefore, it was determined that the current (2002) aerial survey results would be compared to the more accurate ground survey results obtained in 1996 to determine armor unit movement. Comparisons of 2002 aerial survey data and 1996 ground survey data are presented in Table 1. In addition, the absolute values of the differences in position and elevations are shown in Table l. The table reveals relatively close comparison between the two surveys indicating minimal horizontal and vertical movement of the targeted concrete armor units. Maximum movement in the horizontal and vertical directions was 0.137 m (0.45 ft) and 0.107 m (0.35 ft), respectively. The average movement of all horizontal and vertical targets, respectively, was 0.012 m (0.04 ft) and 0.021 m (0.07 ft). In general, the vertical movement of targets was slightly greater than the horizontal movements. Seventy-three percent of all vertical movement and 93 percent of horizontal target movement were 0.03 m (0.1 ft) or less.

For the tribars with three targets, a more in-depth analysis was conducted. With the x-, y-, and z- (easting, northing, and el) coordinates defined for each target on the various armor units, the coordinates of the centroid (center of mass) of each targeted armor unit were computed for the 2002 aerial survey. In addition, the position of each armor unit relative to the x-, y-, and z-axes was determined. Figure 20 shows, in three dimensions, the orientation of representative armor units to the three axes. The centroid coordinates of each targeted armor unit and each unit's orientation (rotation angle relative to the x-, y-, and z-axes) are presented in Tables 2 and 3, respectively, and compared with the ground survey results of 1996. Maximum movement of the centroids was 0.089 m (0.29 ft) and 0.073 m (0.24 ft) in the horizontal and vertical directions, while average movements were 0.012 m (0.04 ft) and 0.024 m (0.08 ft) in the horizontal and vertical directions. Changes in the rotation angles of the armor units varied from 0.0 to 4.03 deg with an average of 0.64 deg. Data indicate minimal movement of the targeted armor unit centroids.

Photo maps combine the image characteristics of a photograph with the geometric qualities of a map. The image is rectified and free from skewness and distortion, and therefore, precise horizontal measurements may be obtained using

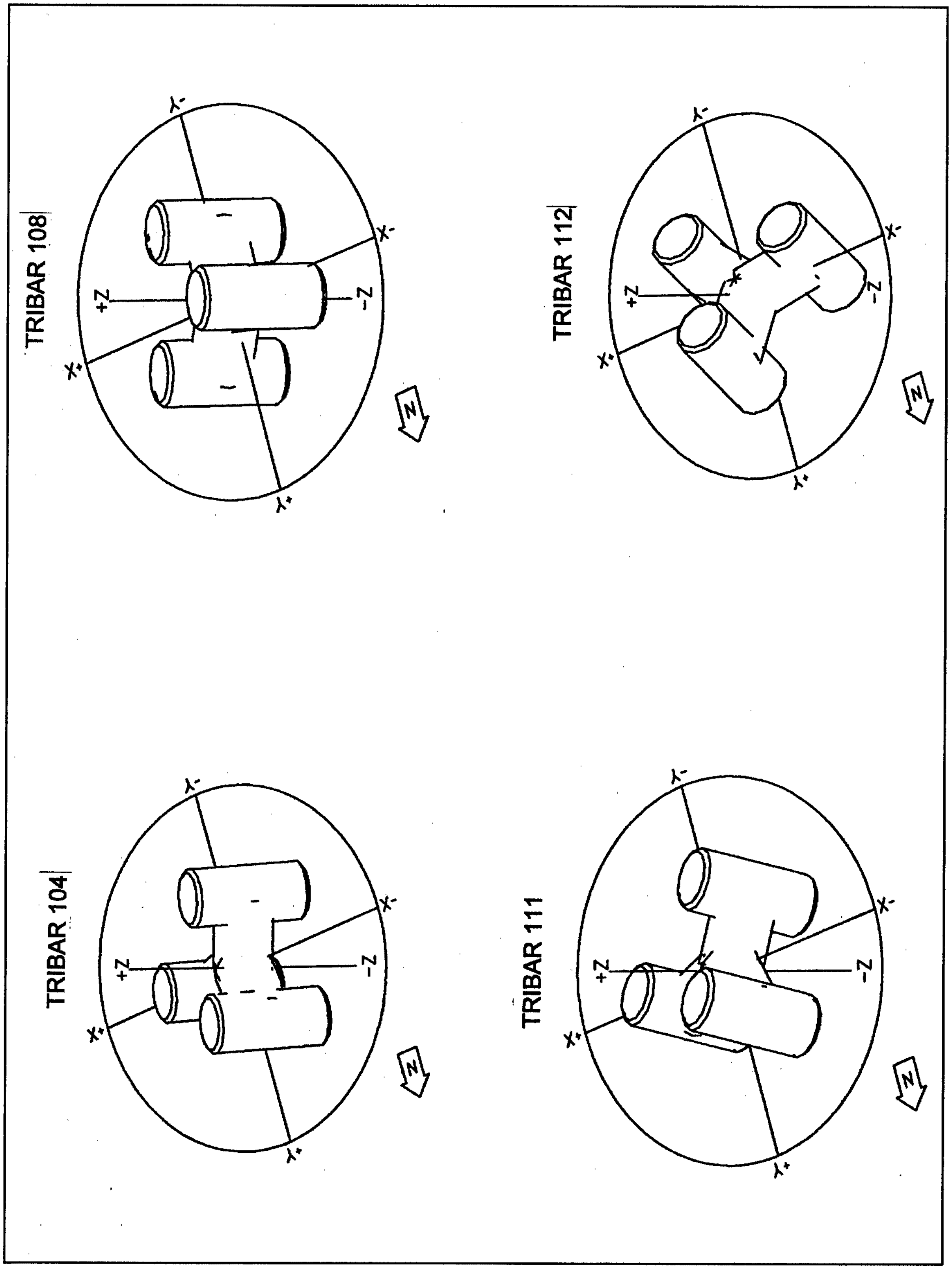

Figure 20. Representative targeted armor unit positions relative to x-, y-, and z-axis

an engineer scale. Photo maps were prepared for the Ofu Harbor breakwater for the 2002 aerial survey. They were produced on Mylar sheets at a scale of 1:240. An example of a photo map of the outer portion of the Ofu breakwater is shown in Figure 21.

In summary, detailed and accurate information relative to the armor unit positions for the Ofu Harbor breakwater have been captured by means of aerial photography and photogrammetric analysis. Comparisons of 2002 target data to that obtained in 1996 indicated horizontal movements ranging from 0.0 to 0.137 m (0.0 to 0.45 ft) and vertical movements ranging from 0.0 to 0.107 m (0.0 to 0.35 ft). Additional comparisons of 2002 centroid data to that of 1996 revealed horizontal movements ranging from 0.0 to 0.088 m (0.0 to 0.29 ft) and vertical movements ranging from 0.0 to 0.073 m (0.0 to 0.24 ft). This data indicate that negligible movement of the targeted concrete armor units occurred between 1996 and 2002. The walking survey of the structure indicated also only slight movement of the concrete underlayer units. The structure is considered to be in excellent condition.

Full-scale hard copies of aerial photographs are on file at the authors' offices at CHL and the Honolulu District. In addition, all photogrammetric compilations and analyses have been stored on diskettes in MICROSTATION files for future use. Data are stored and can be retrieved and compared against data obtained during subsequent monitoring. Thus, armor unit movement may continue to be quantified in future years.

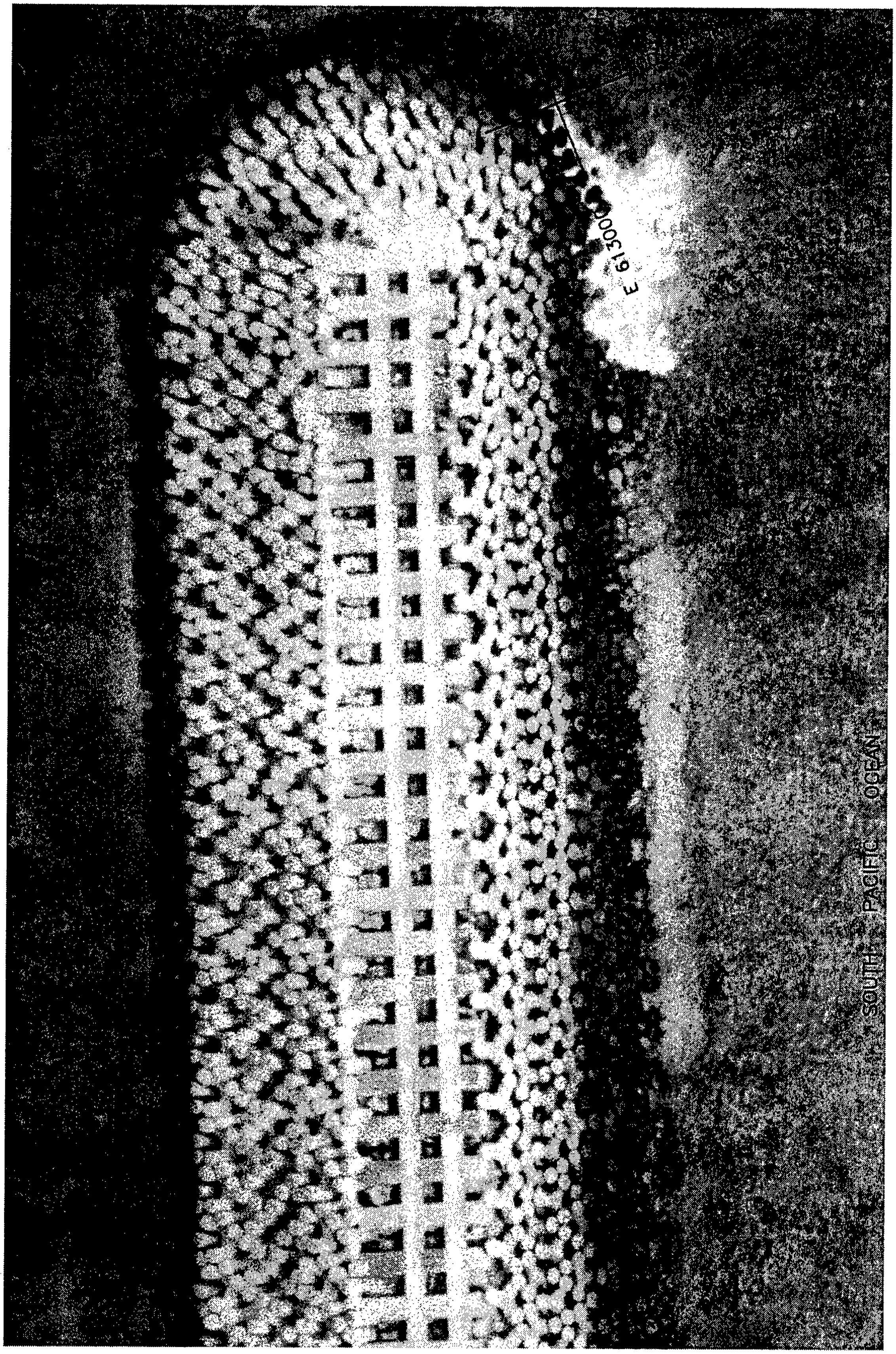

Figure 21. Photo map of outer portion of Ofu breakwater

3 Summary and Findings

Ofu Harbor is subjected to severe storm conditions in the South Pacific, including tropical storms, hurricanes, and cyclones. The original revetment and mole built for harbor protection were damaged several times, and in 1991, were almost completely destroyed. As a result a new breakwater was constructed in 1994 that included the use of 4,080-kg (4.5-ton) concrete tribar armor units. Various concrete underlayer units were developed and used in the structure since additional local stone was not available. No sound, quantifiable data relative to the movement or positions of the concrete armor units had been obtained for the structure prior to this study.

Sound, quantifiable ground survey data relative to the positions of the concrete armor units were initially obtained in 1996 under the "Periodic Inspections" work unit of the MCNP Program. These data established precise base level conditions for the Ofu Harbor breakwater. Logistical problems were encountered attempting to obtain low-altitude aerial photography in this remote location in 1996. The planned low-altitude photography was not obtained, however, oblique images taken from a fixed-wing aircraft were analyzed using convergent photogrammetric techniques, which proved to be acceptable but not as accurate as the planned work, and thus not used to compare to 2002 data.

During the current survey (2002), low-altitude photography was obtained and the accuracy of the photogrammetric analysis was validated and defined through comparison with ground survey data on control points and targets established on the structure. A procedure using high resolution, stereo aerial photographs, a stereoplotter, and MICROSTATION-based software was developed to analyze the entire above-water armor unit fields and quantify armor positions. A detailed walking survey of the structure conducted during the effort also resulted in a well-documented data set that can be compared to previous and subsequent surveys.

Aerial survey data obtained during the 2002 survey were compared with the 1996 ground data obtained previously. An analysis of these data indicates negligible movement of the concrete armor units on Ofu Harbor breakwater. Maximum movement of the targets established on the tribar armor units in the horizontal and vertical directions, respectively, were 0.137 m (0.45 ft) and 0.107 m (0.35 ft); and the average movement of all horizontal and vertical targets were 0.012 m (0.04 ft) and 0.021 m (0.07 ft). Maximum movement of the targeted armor unit centroids were 0.088 m (0.29 ft) and 0.073 m (0.24 ft) in the horizontal and vertical directions, respectively, while average movements were

0.012 m (0.04 ft) and 0.024 m (0.08 ft) in the horizontal and vertical directions. The current (2002) walking inspection revealed more widespread separations between the "cheese block" concrete underlayer units relative to the 1996 inspection; however, most of the separations were less than 0.09 m (0.3 ft). No armor unit breakage was noted. Overall, the structure appeared to be in excellent condition.

The Ofu Harbor breakwater will be revisited in the future under the Periodic Inspections work unit to gather data by which continued assessments can be made on the long-term response of the structure to its environment. The insight gathered from these efforts will allow engineering decisions to be made, based on sound data, as to whether or not closer surveillance and/or repair of the structure might be required to reduce its chances of failing catastrophically. Also, the periodic inspection methods developed and validated for this structure may be used to gain insight into other Corps structures.

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Table 1
Comparison of 2002 and 1996 Survey Data

Target ID	2002 Aerial Survey			1996 Ground Survey			Absolute Value of Differences Between 2002 and 1996 Surveys		
	Easting (E02)	Northing (N02)	Elevation (El02), m (ft)	Easting (E96)	Northing (N96)	Elevation (El96), m (ft)	E02-E96, cm (ft)	N02-N96, cm (ft)	El02-El96, cm (ft)
101A	613107.81	347894.36	4.82 (15.83)	613107.77	347894.34	4.81 (15.77)	1.22 (0.04)	0.61 (0.02)	1.83 (0.06)
101B	613111.43	347895.49	4.11 (13.50)	613111.40	347895.43	4.11 (13.48)	0.91 (0.03)	1.83 (0.06)	0.61 (0.02)
101C	613110.11	347891.16	4.15 (13.63)	613110.01	347891.16	4.13 (13.55)	3.05 (0.10)	0.00 (0.00)	2.44 (0.08)
102A	613103.23	347868.70	3.81 (12.51)	613103.26	347868.77	3.80 (12.47)	0.91 (0.03)	2.13 (0.07)	1.22 (0.04)
102B	613104.77	347872.97	3.82 (12.52)	613104.75	347873.00	3.81 (12.49)	0.61 (0.02)	0.91 (0.03)	0.91 (0.03)
102C	613107.10	347869.76	3.15 (10.35)	613107.08	347869.79	3.15 (10.34)	0.61 (0.02)	0.91 (0.03)	0.30 (0.01)
103A	613105.91	347852.21	2.22 (7.27)	613105.85	347852.14	2.19 (7.20)	1.83 (0.06)	2.13 (0.07)	2.13 (0.07)
103B	613109.56	347853.85	1.64 (5.37)	613109.55	347853.84	1.61 (5.28)	0.30 (0.01)	0.30 (0.01)	2.74 (0.09)
103C	613108.68	347849.43	1.51 (4.96)	613108.68	347849.41	1.50 (4.93)	0.00 (0.00)	0.61 (0.02)	0.91 (0.03)
104A	613084.27	347833.29	5.01 (16.44)	613084.23	347833.27	4.98 (16.35)	1.22 (0.04)	0.61 (0.02)	2.74 (0.09)
104B	613084.97	347837.64	5.07 (16.63)	613084.88	347837.60	5.05 (16.56)	2.74 (0.09)	1.22 (0.04)	2.13 (0.07)
104C	613087.89	347835.12	4.40 (14.44)	613087.81	347835.12	4.39 (14.41)	2.44 (0.08)	0.00 (0.00)	0.91 (0.03)
105A	613083.61	347813.75	3.86 (12.65)	613083.53	347813.74	3.84 (12.61)	2.44 (0.08)	0.30 (0.01)	1.22 (0.04)
105B	613085.82	347817.65	3.67 (12.05)	613085.69	347817.62	3.67 (12.04)	3.96 (0.13)	0.91 (0.03)	0.30 (0.01)
105C	613087.43	347813.92	3.13 (10.27)	613087.32	347813.90	3.13 (10.27)	3.35 (0.11)	0.61(0.02)	0.00 (0.00)
106A	613086.34	347797.25	2.20 (7.23)	613086.29	347797.30	2.22 (7.27)	1.52 (0.05)	1.52 (0.05)	1.22 (0.04)
106B	613089.92	347798.81	1.57 (5.14)	613089.91	347798.84	1.58 (5.18)	0.30 (0.01)	0.91(0.03)	1.22 (0.04)
106C	613088.80	347794.58	1.51 (4.95)	613088.79	347794.57	1.51 (4.94)	0.30 (0.01)	0.30 (0.01)	0.30 (0.01)
107A	613066.99	347781.40	4.68 (15.37)	613066.96	347781.40	4.69 (15.38)	0.91 (0.03)	0.00 (0.00)	0.30 (0.01)
107B	613070.50	347783.23	4.15 (13.63)	613070.43	347783.21	4.15 (13.63)	2.13 (0.07)	0.61 (0.02)	0.00 (0.00)
107C	613069.88	347778.81	4.06 (13.33)	613069.84	347778.83	4.06 (13.33)	1.22 (0.04)	0.61 (0.02)	0.00 (0.00)

(Sheet 1 of 6)

Table 1 (Continued)

Target ID	2002 Aerial Survey			1996 Ground Survey			Absolute Value of Differences Between 2002 and 1996 Surveys		
	Easting (E02)	Northing (N02)	Elevation (El02), m (ft)	Easting (E96)	Northing (N96)	Elevation (El96), m (ft)	E02-E96, cm (ft)	N02-N96, cm (ft)	El02-El96, cm (ft)
108A	613064.26	347754.76	3.46 (11.36)	613064.21	347754.79	3.47 (11.37)	1.52 (0.05)	0.91 (0.03)	0.30 (0.01)
108B	613068.04	347756.02	2.85 (9.34)	613068.01	347756.00	2.84 (9.31)	0.91 (0.03)	0.61 (0.02)	0.91 (0.03)
108C	613066.68	347751.72	2.81 (9.22)	613066.63	347751.75	2.83 (9.27)	1.52 (0.05)	0.91 (0.03)	1.52 (0.05)
109A	613064.26	347735.68	2.21 (7.24)	613064.13	347735.66	2.23 (7.30)	3.96 (0.13)	0.61 (0.02)	1.83 (0.06)
109B	613067.89	347736.64	1.52 (5.00)	613067.87	347736.64	1.55 (5.09)	0.61 (0.02)	0.00 (0.00)	2.74 (0.09)
109C	613066.48	347732.46	1.55 (5.08)	613066.47	347732.46	1.56 (5.12)	0.30 (0.01)	0.00 (0.00)	1.22 (0.04)
110A	613041.54	347721.48	5.15 (16.89)	613041.60	347721.55	5.12 (16.79)	1.83 (0.06)	2.13 (0.07)	3.05 (0.10)
110B	613045.57	347722.12	4.57 (15.00)	613045.58	347722.10	4.54 (14.89)	0.30 (0.01)	0.61 (0.02)	3.35 (0.11)
110C	613043.82	347718.04	4.62 (15.16)	613043.80	347718.01	4.61 (15.12)	0.61 (0.02)	0.91 (0.03)	1.22 (0.04)
111A	613043.71	347701.75	3.60 (11.80)	613043.67	347701.78	3.58 (11.76)	1.22 (0.04)	0.91 (0.03)	1.22 (0.04)
111B	613047.52	347700.53	3.00 (9.84)	613047.44	347700.58	3.00 (9.83)	2.44 (0.08)	1.52 (0.05)	0.30 (0.01)
111C	613043.99	347697.66	3.08 (10.10)	613043.94	347697.68	3.08 (10.10)	1.52 (0.05)	0.61 (0.02)	0.00 (0.00)
112A	613022.09	347691.18	2.50 (8.21)	613021.88	347691.20	2.51 (8.23)	6.40 (0.21)	0.61 (0.02)	0.61 (0.02)
112B	613023.30	347687.42	1.93 (6.34)	613023.25	347687.39	1.90 (6.23)	1.52 (0.05)	0.91 (0.03)	3.35 (0.11)
112C	613019.00	347688.73	1.89 (6.19)	613018.97	347688.68	1.84 (6.03)	0.91 (0.03)	1.52 (0.05)	4.88 (0.16)
113A	613017.00	347706.77	3.93 (12.90)	613017.19	347707.15	3.94 (12.94)	5.79 (0.19)	11.58 (0.38)	1.22 (0.04)
113B	613017.05	347702.49	3.63 (11.90)	613017.50	347702.85	3.69 (12.11)	13.72 (0.45)	10.97 (0.36)	6.40 (0.21)
113C	613013.53	347705.01	3.31 (10.86)	613013.81	347705.07	3.34 (10.96)	8.53 (0.28)	1.83 (0.06)	3.05 (0.10)
114A	613019.97	347732.53	3.51 (11.51)	613019.98	347732.52	3.49 (11.44)	0.30 (0.01)	0.30 (0.01)	2.13 (0.07)
114B	613016.43	347732.56	2.71 (8.90)	613016.39	347732.60	2.68 (8.80)	1.22 (0.04)	1.22 (0.04)	3.05 (0.10)
114C	613018.71	347736.33	2.89 (9.49)	613018.69	347736.36	2.88 (9.44)	0.61 (0.02)	0.91 (0.03)	1.52 (0.05)

Table 1 (Continued)

Target ID	2002 Aerial Survey			1996 Ground Survey			Absolute Value of Differences Between 2002 and 1996 Surveys		
	Easting (E02)	Northing (N02)	Elevation (El02), m (ft)	Easting (E96)	Northing (N96)	Elevation (El96), m (ft)	E02-E96, cm (ft)	N02-N96, cm (ft)	El02-El96, cm (ft)
115A	613021.23	347754.53	2.16 (7.09)	613021.23	347754.53	2.12 (6.97)	0.00 (0.00)	0.00 (0.00)	3.66 (0.12)
115B	613017.73	347753.05	1.44 (4.73)	613017.73	347753.05	1.41 (4.64)	0.00 (0.00)	0.00 (0.00)	2.74 (0.09)
115C	613019.02	347757.36	1.37 (4.49)	613019.02	347757.36	1.33 (4.37)	0.00 (0.00)	0.00 (0.00)	3.66 (0.12)
116A	613037.08	347774.59	3.95 (12.95)	613037.06	347774.54	3.91 (12.83)	0.61 (0.02)	1.52 (0.05)	3.66 (0.12)
116B	613035.38	347770.49	3.86 (12.65)	613035.40	347770.45	3.83 (12.57)	0.61 (0.02)	1.22 (0.04)	2.44 (0.08)
116C	613033.34	347773.90	3.22 (10.55)	613033.31	347773.83	3.21 (10.53)	0.91 (0.03)	2.13 (0.07)	0.61 (0.02)
117A	613044.95	347801.22	3.59 (11.77)	613044.98	347801.14	3.58 (11.73)	0.91 (0.03)	2.44 (0.08)	1.22 (0.04)
117B	613041.29	347800.40	2.83 (9.30)	613041.32	347800.32	2.84 (9.33)	0.91 (0.03)	2.44 (0.08)	0.91 (0.03)
117C	613042.89	347804.48	2.88 (9.45)	613042.88	347804.41	2.88 (9.45)	0.30 (0.01)	2.13 (0.07)	0.00 (0.00)
118A	613046.94	347820.86	2.48 (8.14)	613046.89	347820.84	2.46 (8.06)	1.52 (0.05)	0.61 (0.02)	2.44 (0.08)
118B	613045.45	347816.51	2.53 (8.30)	613045.52	347816.55	2.51 (8.22)	2.13 (0.07)	1.22 (0.04)	2.44 (0.08)
118C	613043.27	347819.61	1.83 (6.02)	613043.27	347819.61	1.79 (5.86)	0.00 (0.00)	0.00 (0.00)	4.88 (0.16)
119A	613064.10	347836.03	4.77 (15.64)	613064.13	347836.10	4.76 (15.61)	0.91 (0.03)	2.13 (0.07)	0.91 (0.03)
119B	613060.37	347835.43	4.03 (13.22)	613060.36	347835.45	4.02 (13.20)	0.30 (0.01)	0.61 (0.02)	0.61 (0.02)
119C	613062.23	347839.45	4.06 (13.32)	613062.23	347839.48	4.04 (13.25)	0.00 (0.00)	0.91 (0.03)	2.13 (0.07)
120A	613067.77	347863.49	3.52 (11.54)	613067.77	347863.49	3.46 (11.35)	0.00 (0.00)	0.00 (0.00)	5.79 (0.19)
120B	613063.99	347862.60	2.83 (9.29)	613064.01	347862.63	2.78 (9.11)	0.61 (0.02)	0.91 (0.03)	5.49 (0.18)
120C	613065.76	347866.81	2.87 (9.40)	613065.75	347866.77	2.82 (9.24)	0.30 (0.01)	1.22 (0.04)	4.88 (0.16)
121A	613066.47	347878.44	2.23 (7.32)	613066.47	347878.44	2.18 (7.15)	0.00 (0.00)	0.00 (0.00)	5.18 (0.17)
121B	613062.81	347877.46	1.54 (5.05)	613062.78	347877.47	1.49 (4.89)	0.91 (0.03)	0.30 (0.01)	4.88 (0.16)
121C	613064.21	347881.63	1.53 (5.03)	613064.21	347881.63	1.50 (4.92)	0.00 (0.00)	0.00 (0.00)	3.35 (0.11)

Table 1 (Continued)

Target ID	2002 Aerial Survey			1996 Ground Survey			Absolute Value of Differences Between 2002 and 1996 Surveys		
	Easting (E02)	Northing (N02)	Elevation (El02), m (ft)	Easting (E96)	Northing (N96)	Elevation (El96), m (ft)	E02-E96, cm (ft)	N02-N96, cm (ft)	El02-El96, cm (ft)
122A	613086.01	347896.85	4.90 (16.08)	613085.99	347896.88	4.88 (16.00)	0.61 (0.02)	0.91 (0.03)	2.44 (0.08)
122B	613082.40	347896.51	4.10 (13.46)	613082.38	347896.55	4.06 (13.31)	0.61 (0.02)	1.22 (0.04)	4.57 (0.15)
122C	613084.38	347900.49	4.31 (14.14)	613084.41	347900.57	4.27 (14.02)	0.91 (0.03)	2.44 (0.08)	3.66 (0.12)
123A	613088.01	347919.33	3.45 (11.32)	613088.02	347919.35	3.39 (11.13)	0.30 (0.01)	0.61 (0.02)	5.79 (0.19)
123B	613084.22	347918.65	2.77 (9.09)	613084.25	347918.61	2.73 (8.97)	0.91 (0.03)	1.22 (0.04)	3.66 (0.12)
123C	613086.03	347922.76	2.81 (9.21)	613086.04	347922.75	2.76 (9.06)	0.30 (0.01)	0.30 (0.01)	4.57 (0.15)
124A	613091.01	347947.15	2.11 (6.91)	613091.01	347947.15	2.00 (6.56)	0.00 (0.00)	0.00 (0.00)	10.67 (0.35)
124B	613087.17	347946.28	1.42 (4.65)	613087.21	347946.25	1.38 (4.52)	1.22 (0.04)	0.91 (0.03)	3.96 (0.13)
124C	613088.74	347950.39	1.38 (4.54)	613088.74	347950.39	1.35 (4.44)	0.00 (0.00)	0.00 (0.00)	3.05 (0.10)
125A	613110.08	347965.35	4.68 (15.35)	613110.12	347965.44	4.65 (15.27)	1.22 (0.04)	2.74(0.09)	2.44 (0.08)
125B	613106.52	347964.84	3.90 (12.81)	613106.54	347964.85	3.87 (12.69)	0.61 (0.02)	0.30 (0.01)	3.66 (0.12)
125C	613108.54	347968.86	3.99 (13.09)	613108.50	347968.91	3.96 (12.98)	1.22 (0.04)	1.52 (0.05)	3.35 (0.11)
126A	613111.12	347987.03	3.43 (11.24)	613111.12	347986.98	3.40 (11.14)	0.00 (0.00)	1.52 (0.05)	3.05 (0.10)
126B	613107.27	347986.79	2.72 (8.92)	613107.38	347986.79	2.69 (8.82)	3.35 (0.11)	0.00 (0.00)	3.05 (0.10)
126C	613109.48	347990.70	2.87 (9.41)	613109.53	347990.72	2.84 (9.33)	1.52 (0.05)	0.61 (0.02)	2.44 (0.08)
127A	613110.22	348002.61	2.21 (7.24)	613110.24	348002.66	2.14 (7.03)	0.61 (0.02)	0.15 (0.05)	6.40(0.21)
127B	613106.62	348002.37	1.45 (4.76)	613106.62	348002.37	1.41 (4.61)	0.00 (0.00)	0.00 (0.00)	4.57 (0.15)
127C	613108.60	348006.37	1.56 (5.11)	613108.60	348006.37	1.52 (4.99)	0.00 (0.00)	0.00 (0.00)	3.66 (0.12)
128A	613128.17	348014.35	4.69 (15.40)	613128.15	348014.32	4.68 (15.34)	0.61 (0.02)	0.91 (0.03)	1.83 (0.06)
128B	613124.34	348014.21	4.02 (13.19)	613124.40	348014.23	4.02 (13.18)	1.83 (0.06)	0.61 (0.02)	0.30 (0.01)
128C	613126.64	348018.09	4.17 (13.69)	613126.62	348018.07	4.16 (13.65)	0.61 (0.02)	0.61 (0.02)	1.22 (0.04)

Table 1 (Continued)

Target ID	2002 Aerial Survey			1996 Ground Survey			Absolute Value of Differences Between 2002 and 1996 Surveys		
	Easting (E02)	Northing (N02)	Elevation (El02), m (ft)	Easting (E96)	Northing (N96)	Elevation (El96), m (ft)	E02-E96, cm (ft)	N02-N96, cm (ft)	El02-El96, cm (ft)
129A	613125.01	348038.36	2.68 (8.78)	613125.02	348038.26	2.67 (8.75)	0.30 (0.01)	3.05 (0.10)	0.91 (0.03)
129B	613123.15	348034.21	2.52 (8.28)	613123.20	348034.23	2.50 (8.21)	1.52 (0.05)	0.61 (0.02)	2.13 (0.07)
129C	613121.22	348037.78	1.97 (6.47)	613121.19	348037.76	1.96 (6.43)	0.91 (0.03)	0.61 (0.02)	1.22 (0.04)
130A	613134.26	348071.09	2.42 (7.93)	613134.26	348071.09	2.33 (7.64)	0.00 (0.00)	0.00 (0.00)	8.84 (0.29)
130B	613130.51	348070.43	1.65 (5.42)	613130.51	348070.43	1.64 (5.38)	0.00 (0.00)	0.00 (0.00)	1.22 (0.04)
130C	613132.21	348074.40	1.72 (5.63)	613132.21	348074.40	1.68 (5.51)	0.00 (0.00)	0.00 (0.00)	3.66 (0.12)
131A	613152.29	348082.25	4.40 (14.44)	613152.18	348082.16	4.40 (14.43)	3.35 (0.11)	2.74(0.09)	0.30 (0.01)
131B	613148.21	348081.97	3.75 (12.31)	613148.19	348081.94	3.75 (12.30)	0.61 (0.02)	0.91 (0.03)	0.30 (0.01)
131C	613150.43	348085.90	3.88 (12.74)	613150.37	348085.90	3.88 (12.74)	1.83 (0.06)	0.00 (0.00)	0.00 (0.00)
132A	613150.69	348098.13	3.36 (11.04)	613150.71	348098.13	3.35 (11.00)	0.61 (0.02)	0.00 (0.00)	1.22 (0.04)
132B	613146.91	348097.81	2.65 (8.71)	613146.90	348097.78	2.66 (8.74)	0.30 (0.01)	0.91 (0.03)	0.91(0.03)
132C	613149.02	348101.81	2.79 (9.15)	613148.96	348101.85	2.77 (9.10)	1.83 (0.06)	1.22 (0.04)	1.52 (0.05)
133A	613150.34	348114.57	2.25 (7.37)	613150.34	348114.57	2.23 (7.33)	0.00 (0.00)	0.00 (0.00)	1.22 (0.04)
133B	613146.70	348115.04	1.50 (4.93)	613146.70	348115.04	1.45 (4.77)	0.00 (0.00)	0.00 (0.00)	4.88 (0.16)
133C	613149.15	348118.62	1.77 (5.80)	613149.15	348118.62	1.76 (5.76)	0.00 (0.00)	0.00 (0.00)	1.22 (0.04)
19	613115.90	347866.35	1.18 (3.88)	613115.86	347866.31	1.18 (3.86)	1.22 (0.04)	1.22 (0.04)	0.61 (0.02)
20	613104.60	347833.17	1.13 (3.71)	613104.54	347833.03	1.11 (3.65)	1.83 (0.06)	4.27 (0.14)	1.83(0.06)
21	613091.14	347800.60	1.45 (4.75)	613091.14	347800.60	1.47 (4.81)	0.00 (0.00)	0.00 (0.00)	1.83 (0.06)
22	613079.27	347764.38	1.17 (3.84)	613079.22	347764.36	1.17 (3.85)	1.52 (0.05)	0.61 (0.02)	0.30 (0.01)
23	613068.27	347733.12	1.26 (4.13)	613068.31	347733.16	1.26 (4.13)	1.22 (0.04)	1.22 (0.04)	0.00 (0.00)
24	613056.29	347698.03	1.07 (3.52)	613056.29	347698.03	1.07 (3.52)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)

Table 1 (Concluded)

Target ID	2002 Aerial Survey			1996 Ground Survey			Absolute Value of Differences Between 2002 and 1996 Surveys		
	Easting (E02)	Northing (N02)	Elevation (EI02), m (ft)	Easting (E96)	Northing (N96)	Elevation (EI96), m (ft)	E02-E96, cm (ft)	N02-N96, cm (ft)	EI02-EI96, cm (ft)
25	613026.27	347682.85	1.14 (3.73)	613026.24	347682.84	1.13 (3.72)	0.91 (0.03)	0.30 (0.01)	0.30 (0.01)
26	613004.51	347715.91	1.60 (5.24)	613004.55	347715.89	1.59 (5.23)	1.22 (0.04)	0.61 (0.02)	0.30 (0.01)
27	613014.79	347748.30	1.22 (4.01)	613015.11	347748.17	1.22 (4.01)	9.75 (0.32)	3.96 (0.13)	0.00 (0.00)
28	613025.94	347781.54	1.08 (3.54)	613025.98	347781.52	1.05 (3.43)	1.22 (0.04)	0.61 (0.02)	3.35 (0.11)
29	613041.47	347819.48	1.48 (4.84)	613041.47	347819.48	1.48 (4.84)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
30	613051.07	347850.16	1.13 (3.72)	613051.09	347850.20	1.11 (3.65)	0.61 (0.02)	1.22 (0.04)	2.13 (0.07)
31	613064.11	347885.50	1.35 (4.43)	613064.22	347885.45	1.34 (4.39)	3.35 (0.11)	1.52 (0.05)	1.22 (0.04)
32	613077.78	347919.18	1.53 (5.01)	613077.79	347919.07	1.48 (4.86)	0.30 (0.01)	3.35 (0.11)	4.57 (0.15)
33	613089.89	347952.00	1.51 (4.94)	613089.89	347952.23	1.48 (4.85)	0.00 (0.00)	7.01 (0.23)	2.74 (0.09)
34	613099.85	347985.46	1.32 (4.33)	613099.85	347985.46	1.26 (4.13)	0.00 (0.00)	0.00 (0.00)	6.10 (0.20)
35	613113.36	348020.82	1.53 (5.03)	613113.36	348020.82	1.51 (4.97)	0.00 (0.00)	0.00 (0.00)	1.83 (0.06)
36	613124.24	348051.52	1.78 (5.85)	613124.30	348051.52	1.78 (5.85)	1.83 (0.06)	0.00 (0.00)	0.00 (0.00)
37	613136.88	348087.34	1.53 (5.03)	613136.88	348087.34	1.52 (5.00)	0.00 (0.00)	0.00 (0.00)	0.91 (0.03)
38	613148.57	348123.44	1.48 (4.86)	613148.57	348123.44	1.47 (4.81)	0.00 (0.00)	0.00 (0.00)	1.52 (0.05)

(Sheet 6 of 6)

Table 2
Comparison of Centroid Data for 2002 and 1996 Survey Data

Armor Unit ID	2002 Aerial Survey			1996 Ground Survey			Absolute Value of Differences Between 2002 and 1996 Surveys		
	Easting (E02)	Northing (N02)	Elevation (El02), m (ft)	Easting (E96)	Northing (N96)	Elevation (El96), m (ft)	E02-E96, cm (ft)	N02-N96, cm (ft)	El02-El965, cm (ft)
101	613108.63	347894.01	3.86 (12.65)	613108.58	347894.02	3.84 (12.60)	1.52 (0.05)	0.30 (0.01)	1.52 (0.05)
102	613104.02	347870.88	3.06 (10.05)	613104.02	347870.92	3.05 (10.01)	0.00 (0.00)	1.22 (0.04)	1.22 (0.04)
103	613106.99	347852.21	1.26 (4.14)	613106.97	347852.12	1.24 (4.07)	0.61 (0.02)	2.74 (0.09)	2.13 (0.07)
104	613084.67	347835.63	4.29 (14.08)	613084.60	347835.61	4.27 (14.01)	2.13 (0.07)	0.61 (0.02)	2.13 (0.07)
105	613084.60	347815.43	3.01 (9.89)	613084.50	347815.41	3.01 (9.87)	3.05 (0.10)	0.61 (0.02)	0.61 (0.02)
106	613087.20	347797.18	1.25 (4.09)	613087.18	347797.24	1.26 (4.12)	0.61 (0.02)	1.83 (0.06)	0.91 (0.03)
107	613068.11	347781.41	3.76 (12.34)	613068.05	347781.41	3.76 (12.35)	1.83 (0.06)	0.00 (0.00)	0.30 (0.01)
108	613065.27	347754.52	2.51 (8.24)	613065.22	347754.51	2.51 (8.25)	1.52 (0.05)	0.30 (0.01)	0.30 (0.01)
109	613065.09	347735.32	1.24 (4.08)	613065.07	347735.31	1.26 (4.13)	0.61 (0.02)	0.30 (0.01)	1.52 (0.05)
110	613042.74	347720.86	4.22 (13.86)	613042.76	347720.87	4.20 (13.77)	0.61 (0.02)	0.30 (0.01)	2.74 (0.09)
111	613044.37	347700.69	2.67 (8.77)	613044.33	347700.72	2.67 (8.75)	1.22 (0.04)	0.91 (0.03)	0.61 (0.02)
112	613021.84	347690.10	1.57 (5.15)	613021.72	347690.15	1.55 (5.10)	3.66 (0.12)	1.52 (0.05)	1.52 (0.05)
113	613016.67	347705.20	3.06 (10.04)	613016.96	347705.44	3.09 (10.15)	8.84 (0.29)	7.32 (0.24)	3.35 (0.11)
114	613019.50	347733.26	2.54 (8.33)	613019.48	347733.30	2.51 (8.25)	0.61 (0.02)	1.22 (0.04)	2.44 (0.08)
115	613020.59	347754.57	1.18 (3.87)	613020.58	347754.55	1.14 (3.75)	0.30 (0.01)	0.61 (0.02)	3.66 (0.12)
116	613036.34	347772.63	3.15 (10.33)	613036.29	347772.59	3.12 (10.23)	1.52 (0.05)	1.22 (0.04)	3.05 (0.10)
117	613044.23	347801.61	2.60 (8.54)	613044.22	347801.53	2.60 (8.52)	0.30 (0.01)	2.44 (0.08)	0.61 (0.02)
118	613046.27	347818.54	1.76 (5.77)	613046.31	347818.55	1.73 (5.69)	1.22 (0.04)	0.30 (0.01)	2.44 (0.08)
119	613063.36	347836.45	3.79 (12.42)	613063.38	347836.49	3.77 (12.38)	0.61 (0.02)	1.22 (0.04)	1.22 (0.04)
120	613066.95	347863.90	2.56 (8.39)	613066.95	347863.89	2.50 (8.21)	0.00 (0.00)	0.30 (0.01)	5.49 (0.18)
121	613065.62	347878.74	1.26 (4.13)	613065.61	347878.78	1.21 (3.97)	0.30 (0.01)	1.22 (0.04)	4.88 (0.16)

(Continued)

Table 2 (Concluded)

Armor Unit ID	2002 Aerial Survey			1996 Ground Survey			Absolute Value of Differences Between 2002 and 1996 Surveys		
	Easting (E02)	Northing (N02)	Elevation (El02), m (ft)	Easting (E96)	Northing (N96)	Elevation (El96), m (ft)	E02-E96, cm (ft)	N02-N96, cm (ft)	El02-El965, cm (ft)
122	613085.44	347897.58	3.93 (12.91)	613085.46	347897.61	3.90 (12.81)	0.61 (0.02)	0.91 (0.03)	3.05 (0.10)
123	613087.15	347919.80	2.49 (8.17)	613087.16	347919.80	2.44 (8.01)	0.30 (0.01)	0.00 (0.00)	4.88 (0.16)
124	613090.06	347947.46	1.12 (3.68)	613090.01	347947.49	1.05 (3.44)	1.52 (0.05)	0.91 (0.03)	7.32 (0.24)
125	613109.56	347965.80	3.70 (12.15)	613109.59	347965.89	3.68 (12.06)	0.91 (0.03)	2.74 (0.09)	2.74 (0.09)
126	613110.35	347987.78	2.48 (8.13)	613110.39	347987.75	2.45 (8.04)	1.22 (0.04)	0.91 (0.03)	2.74 (0.09)
127	613109.58	348003.25	1.23 (4.05)	613109.58	348003.30	1.18 (3.87)	0.00 (0.00)	1.52 (0.05)	5.49 (0.18)
128	613127.39	348015.15	3.76 (12.34)	613127.37	348015.12	3.75 (12.30)	0.61 (0.02)	0.91 (0.03)	1.22 (0.04)
129	613124.14	348036.52	1.85 (6.07)	613124.16	348036.49	1.84 (6.03)	0.61 (0.02)	0.91 (0.03)	1.22 (0.04)
130	613133.49	348071.55	1.43 (4.68)	613133.41	348071.55	1.37 (4.48)	2.44 (0.08)	0.00 (0.00)	6.10 (0.20)
131	613151.28	348083.05	3.47 (11.38)	613151.21	348082.99	3.47 (11.37)	2.13 (0.07)	1.83 (0.06)	0.30 (0.01)
132	613149.94	348098.83	2.41 (7.92)	613149.89	348098.82	2.40 (7.88)	1.52 (0.05)	0.30 (0.01)	1.22 (0.04)
133	613149.77	348115.67	1.31 (4.30)	613149.81	348115.70	1.29 (4.24)	1.22 (0.04)	0.91 (0.03)	1.83 (0.06)

Table 3
Comparison of Rotation Angles for Targeted Armor Units for 2002 and 1996 Survey Data

Armor Unit ID	2002 Rotation Angle (deg)			1996 Rotation Angle (deg)			Difference Between 2002 and 1996 Rotation Angles (deg)		
	X-axis	Y-axis	Z-axis	X-axis	Y-axis	Z-axis	X-axis	Y-axis	Z-axis
101	-35.72	-1.57	-109.28	-35.93	-0.90	-109.65	0.21	-0.67	0.37
102	-13.84	28.98	-45.31	-13.92	28.72	-45.33	0.08	0.26	0.02
103	-32.81	5.18	-100.06	-32.28	4.43	-99.01	-0.53	0.75	-1.05
104	-11.74	29.59	-34.85	-11.38	29.34	-34.34	-0.36	0.25	-0.51
105	-20.49	24.00	-55.94	-20.27	23.94	-55.83	-0.22	0.06	-0.11
106	-35.29	2.49	-100.44	-35.28	3.12	-100.97	-0.01	-0.63	0.53
107	-30.26	3.89	-96.83	-30.62	3.89	-96.78	0.36	0.00	-0.05
108	-32.83	1.49	-105.91	-32.69	0.51	-106.38	-0.14	0.98	0.47
109	-34.97	-0.95	-111.16	-34.13	-0.39	-110.13	-0.84	-0.56	-1.03
110	-27.55	-2.15	-113.90	-27.45	-2.96	-115.82	-0.10	0.81	1.92
111	-28.61	-3.35	-142.37	-28.32	-3.40	-142.65	-0.29	0.05	0.28
112	-30.94	1.95	163.23	-32.75	2.56	166.23	1.81	-0.61	-3.00
113	-22.93	13.57	150.41	-20.96	15.03	154.44	-1.97	-1.46	-4.03
114	-36.69	-7.65	51.42	-36.26	-8.32	51.15	-0.43	0.67	0.27
115	-40.16	3.07	76.70	-39.94	3.44	76.68	-0.22	-0.37	0.02
116	-18.08	28.37	131.36	-17.42	27.51	131.45	-0.66	0.86	-0.09
117	-37.58	-2.02	66.93	-36.79	-1.57	66.96	-0.79	-0.45	-0.03
118	-12.36	31.65	137.36	-13.02	32.40	137.97	0.66	-0.75	-0.61
119	-37.11	-1.32	63.38	-37.17	-0.64	64.40	0.06	-0.68	-1.02
120	-34.97	-1.47	67.28	-34.78	-1.66	67.21	-0.19	0.19	0.07

(Continued)

Table 3 (Concluded)

Armor Unit ID	2002 Rotation Angle (deg)			1996 Rotation Angle (deg)			Difference Between 2002 and 1996 Rotation Angles (deg)		
	X-axis	Y-axis	Z-axis	X-axis	Y-axis	Z-axis	X-axis	Y-axis	Z-axis
121	-35.79	0.33	69.50	-35.25	-0.39	69.48	-0.54	0.72	0.02
122	-36.00	-8.69	57.86	-36.68	-9.02	57.13	0.68	0.33	0.73
123	-34.26	-1.53	64.53	-33.74	-1.14	65.20	-0.52	-0.39	-0.67
124	-35.16	1.51	68.83	-32.60	1.04	68.80	-2.56	0.47	0.03
125	-38.92	-3.61	59.49	-39.25	-3.69	61.05	0.33	0.08	-1.56
126	-32.52	-6.31	57.99	-32.65	-6.52	56.40	0.13	0.21	1.59
127	-36.16	-4.63	56.10	-35.25	-4.91	57.01	-0.91	0.28	-0.91
128	-31.16	-6.34	56.19	-30.76	-6.07	55.24	-0.4	-0.27	0.95
129	-19.09	24.43	129.92	-19.85	23.93	128.61	0.76	0.5	1.31
130	-37.00	-2.73	65.44	-34.53	-1.73	65.44	-2.47	-1.00	0.00
131	-29.24	-5.53	60.37	-29.30	-5.56	58.79	0.06	0.03	1.58
132	-33.40	-5.58	58.33	-32.56	-4.52	58.77	-0.84	-1.06	-0.44
133	-30.75	-11.56	46.90	-31.32	-12.99	46.94	0.57	1.43	-0.04

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14. ABSTRACT

Selected coastal navigation structures are periodically monitored under the "Periodic Inspections" work unit of the Monitoring Completed Navigation Projects Program. Such monitoring is done to gain an understanding of the long-term structural response of unique structures to their environment. Periodic data sets are used to improve knowledge in design, construction, and maintenance of both existing and proposed coastal navigation projects.

The Ofu Harbor breakwater, American Samoa, was nominated for periodic monitoring by the U.S. Army Engineer District, Honolulu. The positions of the above-water, concrete armor units (tribars) on the breakwater were initially obtained in 1996 through ground surveys, aerial photography, and photogrammetric analysis. The structure was revisited in 2002 to determine changes that had occurred. Results indicated negligible movement of the concrete armor units and no armor unit breakage.

The site will again be revisited in the future and long-term structural response of the structure to its environment will continue to be tracked. This data will facilitate engineering decisions concerning whether or not closer surveillance and/or repair of the breakwater might be required to reduce its chance of failing catastrophically. The periodic inspection methods developed and validated for the Ofu Harbor breakwater may also be used to gain insight into other Corps structures.

15. SUBJECT TERMS

Aerial photography	Concrete armor units	Periodic inspections	Remote sensing
Breakwaters	Ofu Harbor, American Samoa	Photogrammetry	Tribars

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